GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ______

Project No. E-16-682 B. T. ZINN — DATE 7/13/82

Project Director: ~~Dr. Ben T. Zinn~~ ~~Bob Daniel~~ — School/Lab AE

Sponsor: U. S. Dept. of Energy; Pittsburgh, PA 15236

Type Agreement: Grant No. DE-FG22-82PC50257

Award Period: From 6/22/82 To ~~6/21/83~~ 7/21/83 (Performance) 9/21/83 (Reports)

Sponsor Amount: $143,176 — Contracted through:

Cost Sharing: $32,331 (E-16-374) — GTRI/~~GIT~~

Title: Development of a Coal Burning Pulsating Combustor for Industrial Power Generator

ADMINISTRATIVE DATA

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Defense Priority Rating: N/A — Security Classification: N/A

RESTRICTIONS

See Attached DOE Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date January 24, 1984

roject No. E-16-682 School/XXX AE

ncludes Subproject No.(s) NONE

roject Director(s) Dr. Ben Zinn GTRI / XXXX

ponsor Department of Energy - Pittsburgh

itle "Development of a Coal Burning Pulsating Combuster for Industrial Power"

ffective Completion Date: 7/21/83 (Performance) (Reports)

irant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [X] Final Report of Inventions
- [X] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

ontinues Project No. N/A Continued by Project No. N/A

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II. PROGRESS TO DATE

The developed combustor is based upon the principles of the acoustic Rijke Tube[5,6] which consists of a vertical pipe of length L containing a heated metal gauze at a distance L/4 from the bottom of the tube. The pipe is open at both ends and heat transfer from the gauze to the surrounding air results in an upward flow of air (due to buoyancy) and the excitation of the fundamental, longitudinal acoustic mode of the tube. The Rijke type, coal burning pulsating combustor developed under this program is shown in Fig. 1. A coal burning bed located at a distance of L/4 from the bottom of the tube serves as the Rijke tube heat source which excites the fundamental acoustic mode of the combustor indicated by the wave structure shown in Fig. 1. The combustion bed is located in a region where both the acoustic pressure and velocity are nonzero and the interaction between these oscillations and the combustion process establishes a positive feedback loop which provides the energy required for maintaining the oscillations.

Coal is fed into the bed at a preselected rate by an auger-type feed system that is attached to the combustor wall just above the combustion bed. A preselected flow rate of combustion air enters the combustor through the bottom decoupling chamber. Combustion occurs when this air moves through the bed and reacts with the combustible volatiles and the coal. The presence of acoustic velocity oscillations in the bed increases the coal burn rate by improving the efficiencies of the gas phase mixing processes and the transport of oxygen to the coal surface.[7,8,9]

Two auger-type feed systems have been developed under this program to date, see Fig. 2. The auger shown in the right of Fig. 2 was developed later on in the program after it had been found that the auger on the left of Fig. 2 produced an undesirable periodic coal feed rate which, in turn, resulted in periodic variation of the air/fuel ratio in the combustion zone. The desired coal feed rate is established by controlling the rate of rotation of the auger. Thus, by controlling the coal and air supply rates, testing at different air/fuel ratios can be performed.

The measurements performed during a given test are described in Fig. 1. A pressure transducer at the midpoint of the combustor, where the acoustic pressure antinode is located, measures the amplitude of the pulsations. The gas temperatures near the entrance to the combustor, above the combustion bed and below the exit plane are measured with thermocouples as shown. Probes for sampling gas and particulates from the exhaust flow are located just below the combustor exit plane, see Fig. 3. A schematic of the exhaust gas and particulate sampling trains are presented in Fig. 4. The exhaust gas is sampled continuously and analyzed to determine the CO, CO_2, NO_x and SO_2 concentrations in the exhaust flow. Particulate sampling is performed isokinetically to determine the exhaust flow particulates concentration at selected periods during testing. A mini computer based data acquisition and storage system has been developed which digitizes the analog test data and stores it for post test analysis and plotting. Consequently, the performance of the combustor throughout the duration of a test can be continuously recorded and analyzed. More details about the developed instrumentation system can be found in a recently completed Ph.D. thesis[10] that was performed as part of this research program.

To date, the performance of the combustor was evaluated over a range of coal feed rates and air/fuel ratios using a bituminous coal with an average ultimate analysis as given below:

	As Received	Dry Basis
% Moisture:	1.65	-
% Carbon:	77.16	78.46
% Hydrogen:	4.95	5.03
% Nitrogen:	1.35	1.37
% Chlorine:	0.04	0.05
% Sulphur:	2.09	2.13
% Ash:	5.37	5.46
% Oxygen (diff.):	7.39	7.50

Lower calorific value: 13,900 Btu/lb.

The stoichiometric air/fuel ratio for this coal is 10.35. This value was determined under the assumption that all carbon reacts to form carbon dioxide, all sulphur reacts to form sulphur dioxide, and all hydrogen reacts to form water vapor.

Tests conducted under this study to date have demonstrated that unpulverized coal can be burned continuously under a pulsating mode of combustion in the developed Rijke type combustor. Pulsating operating is achieved consistently within minutes after igniting the combustion bed. Completely different characteristics of burning under pulsating and non pulsating conditions were observed.

Under the pulsating mode of operation, the flames above the combustion bed were relatively short and exhibited an intense agitation. The coal in the bed was totally immersed in the flames and "dancing", downward pointing flamelets were anchored to the bottom of the combustion bed. In addition, the exhaust flow appeared clear and smoke free. Finally, the combustor wall in the region of the combustion bed heated up very rapidly (after ignition) to a glowing red condition.

During the course of this investigation it has been noted that opening a 1/2 inch hole in the combustor wall approximately 1 foot above the combustion bed caused a transition to nonpulsating burning. When the pulsations stopped the flames became relatively long, sometimes reaching the top of the 9 foot combustor, and the base of the flames appeared to be attached to the coal at some distance above the metal grid that supports the bed. Also, the flames lacked the agitation observed during pulsating operation and rapid accumulation of unburned coal occurred in the bed. The exhaust gases were smoky and the wall surrounding the burning bed was not as hot during operations without pulsations.

The observed qualitative differences between the pulsating and nonpulsating modes of operation support arguments in the literature which indicate that the presence of pulsations improves the efficiencies of the combustion and heat transfer processes. The oscillatory flow in the combustion zone improves the mixing between oxidizer and fuel, which results in a higher reaction rate and a more complete combustion process. The latter is responsible for the observed short flames and the clear and apparently smoke free exhaust gases. The back-and-forth velocity oscillations in the combustion zone are also responsible for the presence of the highly agitated flames that engulf the coal in the bed and, also for the flamelets that extend downward from the bottom of the metal grid that supports the bed. Finally, support for the intensification of heat transfer under pulsating conditions is provided by the observed rapid heat-up of the combustor wall surrounding the reaction zone.

A typical set of test data is presented in Figs. 5 through 10. The pressure amplitude variations with time, shown in Fig. 5, remains relatively constant with time. However, the data exhibits step-function changes because of round-off errors in the data reduction program. The program is currently being modified to reduce the round-off errors and provide a more representive output of the pressure data. Figures 6,7,8 and 9 show the time variations of the exhaust flow concentrations of CO, CO_2, NO_x and SO_2, respectively. The fluctuations in the concentration measurements have been correlated with the periodic discharges of coal during each revolution of the coal feed auger. Modifications to the coal feed system are in progress which should provide a more uniform coal feed rate and decrease the fluctuations in the concentration measurements.

Figure 10 shows the time variations of the temperatures at different combustor locations. Temperature T_2 was measured 1 ft. above the combustion bed and the remaining temperatures were measured 1 ft. below the combustor exit plane, at the radial locations shown in Fig. 11. The temperature data indicate that temperatures inside the combustor are relatively low. For example, note that T_2, the temperature 1 ft. above the burning bed, is only around $1400^{\circ}F$, which is considerably lower than the $3000^{\circ}F$ temperatures that are expected in coal combustors.[1,2] The reasons for the measured low temperatures is that the developed steel combustor was not insulated and the presence of acoustic velocity oscillations resulted in high heat losses through the combustor walls.

The performance under each test condition was determined from time averages, over the duration of the test, of data similar to that presented in Figs. 5 through 10. Typical results are presented herein and more data can be found in Ref. 10. The following set of data was obtained with the inclined auger on the left of Fig. 2. These tests were conducted with a nominal coal feed rate of 50 gr/min and different air/fuel ratios. The measured CO and CO_2 concentrations together with the air/fuel ratio were used to determine the combustor efficiency η. Typical dependence of η upon the nondimensional air/fuel ratio α is presented in Fig. 12. As expected, η increases with α and it is larger than 96% for $\alpha = 1.15$, which compares very favorably with coal burning stokers. The latter usually operate at 20 - 30% excess air and typically have a carbon loss of 4 to 8%, depending on the amount of reinjection.[2] No reinjection of unburned refuse was performed in any of the experiments of this investigation.

Figure 13 shows the dependence of the average dB level of oscillations upon the nondimensional air/fuel ratio. The data show that maximum amplitudes occur near stoichiometric air/fuel ratio. It is believed that this behavior is related to the magnitude of the temperature change, from cold air to hot combustion products, that occurs at the bed. This temperature jump is maximum near stoichiometric operation and it has been shown[11,15,16] that the efficiency of driving acoustic waves in tubes with a temperature jump (see Fig. 18) increases when the magnitude of the temperature jump increases. The results shown in Fig. 13 also indicate that a Rijke type combustor can be operated at high amplitudes of pulsation with little excess air. This result suggests that systems utilizing such a combustor should exhibit high thermal efficiencies. Furthermore, Fig. 13 shows that pulsating combustion of coal is possible in a Rijke type combustor over a wide range or air/fuel ratios. Since for $\alpha = 1$, the exhaust flow contains combustibles, these data suggest that the pulsating combustor could possibly be used as a coal gasifier.

For the following series of tests the inclined auger was replaced by the horizontal auger on the right of Fig. 2. The new auger provided a much more uniform coal feed rate into the combustion bed and it was used to investigate the dependence of the combustor performance upon the coal feed rate for fixed values of the normalized air/fuel ratio. Two normalized air/fuel ratios were tested; that is, $\alpha = 1.00$ and $\alpha = 1.13$. The coal feed rate was increased from 36 to 90 gr/min (28.9 to 72.2 lb/ft^{2}hr) in steps of approximately 8-10 gr/min (6.4 - 8.0 lb/ft^{2}hr).

Results obtained in this series of tests are presented in Figs. 14 through 17. Figure 14 describes the dependence of the combustion efficiency η upon the coal feed rate. It shows that for $\alpha = 1.00$, the maximum efficiency is 92% and 90% for feed rates ranging between 42.1 - 56.1 lb/ft^{2}hr. On the other hand, $\eta = 95\%$ for $\alpha = 1.13$ and coal feed rates in the range 42 - 60 lb/ft^{2}hr, with η reaching a maximum value of 97%. Again, these results compare very favorably with characteristic combustion efficiencies of stokers.[2]

The trends indicated by the data presented in Fig. 14 can be understood with the aid of the results presented in Fig. 15 which describes the dependence of the average dB level of pulsations on the coal feed rate. Figure 15 shows that the dB level of pulsations increases monotonically with an increase in the coal feed rate for a constant α. Furthermore, as expected (see Fig. 15), the amplitudes produced under stoichiometric conditions are, in general, larger than those for $\alpha = 1.13$. The lower acoustic pressure amplitudes at the lower feed rates results in a reduction in the intensity of mixing between the oxidizer and the fuel which is probably the reason for the decrease in the observed combustion efficiencies (see Fig. 14). As the fuel feed rate increases (for a fixed air/fuel ratio) the dB level of pulsations increases and there is theoretical evidence* that the higher amplitude acoustic oscillations , in addition to the higher steady air velocities, cause elutriation of small burning particles. Indeed, the presence of particles in the exhaust flow was observed in tests conducted at the higher feed rates. The presence of burning particles in the exhaust flow is believed to have been the main cause of the observed decrease in combustion efficiencies at the higher coal feed rates. The combustion efficiency data were used to determine the combustor's heat release rates which are shown in Fig. 16. The heat release rates, Q, in MBtu/ft^{2}hr, were computed from the following formula:

$$Q = \frac{HV \times m_F \times \eta}{A} = 111.46\ m_F\ \eta$$

where m_F is in gr/min and η is in percent.

Figure 16 shows that a maximum heat release rate of approximately 0.87 MBtu/ft^{2}hr; this is higher or comparable to heat release rates of other state-of-the-art combustors.[2]

The dependence of NO_x formation upon the coal feed rate is presented in Fig. 17 for different values of m_F. For comparison with the government's New Source Performance Standards (NSPS) of 1971 and 1979 the data is expressed in terms of lb NO_x per 10^6 Btu. Figure 17 shows that for $\alpha = 1.13$ the NO_x production slightly exceeds the 1979 NSPS standard for feed rates up to, approximately, 48 lb/ft^{2}hr with a higher production of

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* Obtained from an analysis computation performed under this program.

NO_x occurring at higher feed rates. Figure 17 also indicates that for a given coal feed rate, the NO_x production increases with increased excess air (i.e., α) and it is below the 1979 NSPS standard for stoichiometric operation (i.e., $\alpha = 1$). These results indicate that the NO_x production in the developed combustor could be further reduced by staging the combustion process, as was done in related studies.[2,4]

In summary, the results presented in this section demonstrate that coal can be burned efficiently in a Rijke type pulsating combustor. The high combustion efficiencies were obtained in spite of the fact that the combustor was uninsulated, which resulted in high heat losses (which are recoverable) through the combustor walls and relatively low temperatures in the combustion zone. Furthermore, these high combustion efficiencies were achieved with the combustor operated with relatively little excess air (i.e., 13%). Finally, the NO_x production only slightly exceeded the 1979 NSPS standards for coal feed rates up to 48 lb/ft^2hr and it decreased with decreasing excess air values.

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September 30, 1982

Mr. Harry Ritz
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Subject: Progress report for the period June 22, 1982 through Sept. 30, 1982 for work conducted under Contract No. DE-A 505-79 10068.

Dear Mr. Ritz:

This progress report highlights the activities conducted since the renewal of DOE Contract No. DE-A 505-79 10068 which supports the "Development of Coal Burning Pulsating Combustor for Power Generation". The period covered by this report extends from June 22, 1982 to Sept. 30, 1982.

To satisfy some of the contract requirements, a Beckman model 951 NO/NO_x chemiluminescent analyzer and a Beckman model 865 SO_2 non dispersive infrared analyzer were purchased. These instruments will be used to determine the concentration levels of nitrogen oxide (NO_x) and sulphur dioxide (SO_2) produced by the developed Rijke tube pulsating combustor under different operation conditions. As in the case of the already utilized Beckman CO and CO_2 infrared analyzers, the use of the NO_x and SO_2 analyzers also requires that the collected samples be dried prior to analysis as the presence of moisture inside these analyzers can cause serious errors in the measured data. While the samples analyzed for NO_x concentration could be dried by the approach utilized in the CO and CO_2 measurements (illustrated with the combined particulate-gas sampling train for CO and CO_2 in the August, 1981 Progress Report), the same approach (utilizing an ice bath and separator) could not be used in the SO_2 concentration measurements. Sulphur dioxide is very soluble in liquid water and the condensation and separation of the water vapor from the sample can also retain a representative amount of SO_2, resulting in lower than actual concentrations measured by the infrared analyzer.

In order to replace the ice bath condenser and separator in the previously utilized gas-particulates sampling train, a Perma Pure dryer that operates under the principle of permeation-distilation was purchased. With the use of such a dryer, water in the analyzed sample is continuously removed as water vapor, thus eliminating the problem of SO_2 retention when the sample is dried. The dryer ordered from Perma Pure was designed to reduce the sample moisture content by a factor of 25.

Next, the combined gas-particulates sampling train that was previously utilized only for CO and CO_2 concentration measurements was modified to satisfy the requirements of the SO_2 sampling and to incorporate the two new analyzers in the sampling system. The modified version of the developed sampling train is illustrated in Fig. 1.

With the arrival of the two new Beckman instruments, the tape recorder and the x-y plotter previously utilized in the data acquisition system (illustrated in the September, 1981 Progress Report) were replaced by a mini computer based analog-to-digital (A/D) data acquisition system. This demanded the development of a special software system to satisfy the data acquisition requirements. It is expected that the use of the A/D converter and associated mini computer disc system will considerably decrease the time necessary for data reduction.

The new sampling train and data acquisition system are already installed and the initiation of testing had to be postponed because of difficulties with purchased calibration gases (for the NO_x analyzer) whose compositions differed from those claimed by their suppliers. This difficulty was discovered when check out of the NO_x analyzer with the purchased gases led to absurd results. Since the gases supplier had guaranteed their composition within 2%, it took approximately 2 weeks to determine that the observed problems could only be associated with the utilization of poorly analyzed calibration gases. Re-analyses of these gases by the same manufacturer produced an error of 13% in the analysis of one of the gases. New calibration gases were ordered from a different company and they are expected to arrive within the next few days.

The next step under this program will be the determination of the NO_x, SO_2, CO and CO_2 concentrations produced by the pulsating combustor when operated with different coal feed rates and different air/fuel ratios. This investigation will follow the test program outlined in our most recent proposal to DOE.

Sincerely,

Ben T. Zinn

BTZ/jj

Legend (Fig. 1)

(1) Cylindrical sintered metal filter (60 μ)-gas sampling

(2) 1/2" diameter probe - isokinetic particulates sampling

(3) Two way valves

(4) Four way valve

(5) Fiberglass filter and housing - retention of 99.7% of particles with diameter greater than 0.3 μ.

(6) Perma Pure model 1412-E heated filter and housing

(7) Perma Pure model PD-750-24 SS dryer

(8) Ice bath

(9) Water separator

(10) Vacuum gauge

(11) Thermocouple

(12) Rotameters

(13) Vacuum/pressure gauge

(14) Regulating valves

(15) Protection filters

(16) Relief valve - adjusted to 9 psig

(17) Dual head diaphram pump

(18) Rotameters with control valve

(19) Three way valves

(20) Pressure gauge

(21) CO and CO_2 Beckman model 864 non dispersive infrared analyzers

(22) SO_2 Beckman model 865 non dispersive infrared analyzer

(23) NO/NO_x Beckman model 951A chemiluminescent analyzer

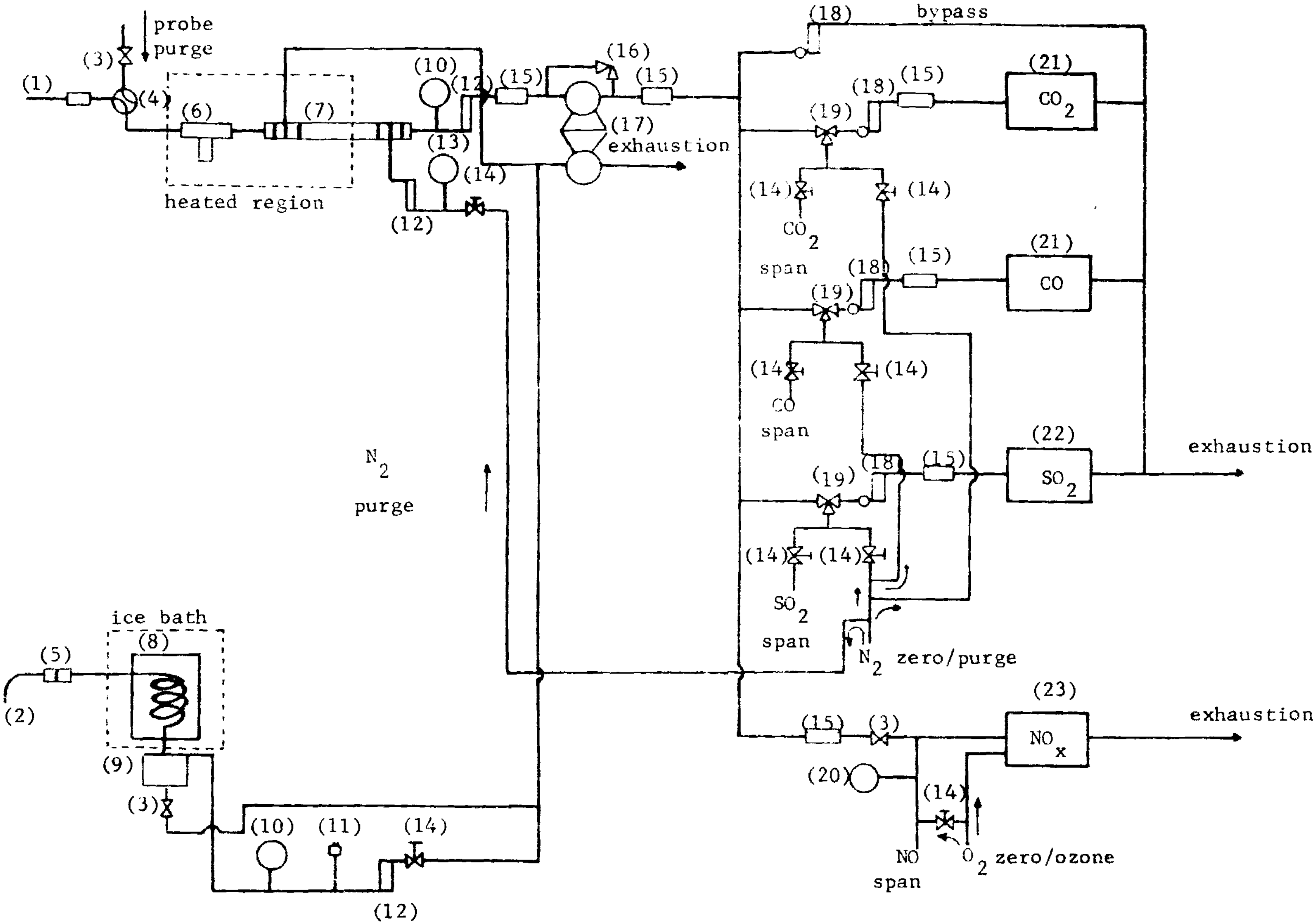

Fig. 1. Modified Gas-Particulate Sampling Train
(legend on next page)

E-16-682

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January 26, 1983

Mr. Harry Ritz
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Subject: Progress report for the period October 1, 1982 through December 31, 1982, for work conducted under Contract No. DE-A 505-79 10068.

Dear Mr. Ritz:

This progress report describes the activities conducted under DOE Contract No. DE-A-505-79-10068 which supports a research program entitled "Development of a Coal Burning Pulsating Combustor for Power Generation". The period covered by the report extends from October 1, 1982 to December 31, 1982.

Upon completion of the installation of the new combined gas-particulates sampling train and of the mini computer based data acquisition system (both described in the last progress report), a series of tests was conducted with the objective of determining the concentrations of NO_x and SO_2 produced by the pulsating combustor under different operating conditions. Specifically, the combustor performance for an average excess of air of 13% and different coal feed rates was investigated.

The output data of a typical experiment, provided by the new data acquisition system, is presented in Figs. 1-6. In the test described in Figs. 1-6, the supply of coal was initiated at $t = 15$ sec and terminated at $t = 26.75$ min. The fluctuations in the measured data are believed to be due to non uniformities in the coal feed rate and their period is basically related to the speed of rotation of the auger which pushes the coal through the feed system. The temperatures presented in Fig. 6 were measured at 1 ft above the bed (T_2) and at three different positions at the section located 1 ft below the combustor's exhaust end. These locations are illustrated by Fig. 7. In this case, the cross section area was divided into three equal concentric parts and a thermocouple probe was placed in the center of each of these areas. The measurements of T_1, T_3, and T_4 provided a measure of the temperature distribution at the indicated location.

Before discussing the NO_x measurement results, a few comments about the origins of this pollutant are in order. Nitrogen oxides generated during the combustion of coal originate in the high temperature oxidation of the nitrogen in the air and in the oxidation of the fuel bound organic nitrogen. The first process produces the so called thermal NO_x and the second the fuel NO_x. The reaction mechanisms leading to the formation of the thermal NO_x are currently well understood and they were first described by Zeldovich[1,2]. The concentration levels of thermal NO_x in the exhaust flow of any combustor can be predicted from the Zeldovich correlation[2]. However, the fuel NO_x constitutes the dominant part of the NO_x generated from coal combustion and very little is known about its origins[1,3]. A quantitative prediction of the fuel NO_x concentration levels in the product gases of coal combustors becomes very difficult because the generated amounts of the pollutants are not only dependent on the coal nitrogen content but also on the coal rank[1].

The test time average NO_x concentrations produced by the pulsating combustor are plotted in Fig. 8. These averages were obtained over the period of time starting from approximately the instant where the combustor attained steady operation (approximately 12 minutes after ignition of the combustion bed in most cases) to the end of the test.
The NO_x concentrations obtained for feed rates lower than 60 gr/min are comparable to those presented by Ref. 4 for tests carried out with a series of different combustors. For example, Ref. 4 reports an average of 437 ppm of NO_x for a spreader-stoker combustor burning a coal with approximately the same nitrogen content as the coal utilized in the present investigation. It can also be observed from Fig. 8 that feed rates higher than approximately 60 gr/min resulted in increased NO_x concentrations in the exhaust gases. The reason for this increase was the occurrence of higher temperatures in the combustion bed which resulted in higher production of thermal NO_x. An indication of the combustion bed temperature increase is given by Fig. 9, which describes the variation of the average temperatures T_1 and T_2 for experiments conducted with different coal feed rates. Figure 9 also presents average temperatures for $\alpha = 1.00$ and $\alpha = 1.13$ which were obtained in tests conducted prior to the development of capabilities for continuous measurements of NO_x and SO_2 concentrations.

The work reported by Ref. 4 dates back to 1967. Since then, stricter regulations have been established to protect the environment from NO_x emissions of power plants. The first federal NO_x limitation corresponded to 0.7 lb/10^6 Btu, set by the New Source Performance Standards (NSPS) of 1971[5,6]. The revised NSPS of 1979 acknowledged the influence of coal composition by setting two NO_x limits: 0.6 lb/10^6 Btu for bituminous coal and 0.5 lb/10^6 Btu for subbituminous coal[6]. These regulations produced a strong economical impact on most power plants whose performance, before 1971, was governed only by combustion efficiency and heat transfer considerations. Before 1971, power plants were producing NO_x at rates as high as 1.5 lb/10^6 Btu.

The measured NO_x concentrations were also used to compute the amounts of NO_x produced per 10^6 Btu. Since practically all of the generated NO converted to NO_2 after emission into the atmosphere, the normal practice has been to calculate the amounts of NO_x as being 100% NO_2[1,5]. The results are illustrated in Fig. 10. Also included in the figure are some NO_x concentrations measured in tests with an average excess air of 0% and 25%. One should note that, as expected, a reduction in the air/fuel ratio to $\alpha = 1.00$ brings the produced amounts of NO_x to acceptable values for feed rates lower than 60 gr/min. It is believed that a major part of the NO_x generated in all of the tests originated in the fuel bound nitrogen and efforts to further reduce the NO_x levels are currently under investigation.

Additional tests were conducted for α approximately equal to 0.88 and 0.76 and a fuel feed rate of 66.5 gr/min. The generated NO_x concentrations were 468 p.p.m. and 363 p.p.m., respectively, which represent a substantial reduction from the concentrations presented in Fig. 8 for the same coal feed rate. These results indicate that the NO_x emission rates may be reduced by staging of the combustion process. Staging[1,5,6] has proven to be successful in a number of reported applications and it is being considered for implementation in the pulsating combustor.

Contrary to what occurs with NO_x, the control of SO_2 formation is not related to combustion control. Sulphur contained within the coal oxidizes directly during the combustion process and the resulting SO_2 is a function of the coal sulphur content and the air/fuel ratio[1,6]. Sulfur dioxide concentrations measured in the exhaust products of the pulsating combustor for tests conducted with $\alpha = 1.13$ are presented in Fig. 11. All of the measured average concentrations were in the range from 835 to 960 p.p.m. (i.e., 900 ppm $\pm$ 7.2%). The variations in the measured data are probably due to the inhomogeneous distribution of the sulphur within the coal. Traces of sulphur are visible on certain particles. The expected inhomogeneity in the distribution of the sulphur content within the coal was verified by an additional ultimate analysis that was performed on the tested coal. For this second ultimate analysis, instead of preparing an average sample, only completely black and "shinny" particles were selected. The analysis showed little variation, from previously measured values, in the coal carbon, hydrogen, and nitrogen contents, but the sulphur content in this second batch was only 0.87% as compared to the 2.09% measured in the first ultimate analysis of the same coal.

The data measured during the reported tests was also utilized to determine the dependence of the combustion efficiency η upon the coal feed rate. Combustion efficiencies were calculated from measurements of CO and CO_2 concentrations in the exhaust flow. The results for $\alpha = 1.00$ and 1.13 are shown in Fig. 12. These data show that for $\alpha = 1.00$, a maximum of 92% was obtained and that combustion efficiency higher than 90 percent was obtained for feed rate in the range between 52.5 and 70 gr/min. On the other hand η was higher than 95% for $\alpha = 1.13$ and coal feed rates in the range 56 to 75 gr/min, with η reaching a maximum value of 97%. The combustion efficiencies were always higher (2.5 to 5%) when the combustor operated with an average 13% excess of air. These results compare very favorably with the characteristic combustion efficiencies reported from stokers that usually operate at 20-30% excess of air and typically have a carbon loss of 4 to 8%, depending on the amount of reinjection(1). No reinjection of unburned refuse was performed in any of the experiments conducted under this program.

The trends shown by the data presented in Fig. 12 can be understood with the aid of the results presented in Fig. 13 which shows the dependence of the average dB level of pulsations on the coal feed rate. It can be observed from Fig. 13 that the dB level of pulsations increases with an increase in the coal feed rate for constant α. Furthermore, the amplitudes produced under stoichiometric conditions (i.e., $\alpha = 1.00$) are in general larger than those for $\alpha = 1.13$. The lower acoustic pressure amplitudes obtained when the combustor operates at feed rates below 50 to 55 gr/min results in a reduction in the intensity of mixing between the oxidizer and the fuel which is probably the reason behind the decrease in the combustion efficiencies in this range of feed rates, see Fig. 12. As the fuel feed rates increase when the air/fuel ratio is kept constant, the dB level of pulsations increase. There is theoretical evidence that the stronger acoustic oscillations act as an additional cause of elutriation of small burning particles[7]. In practice, the presence of particles in the exhaust flow was visible during the tests conducted at the higher feed rates. An increased number of particles, probably still in the process of burning, in the exhaust flow contributed for the decrease in the combustion efficiencies for feed rates higher than 55-60 gr/min.

The work to be conducted during the next reporting period will concentrate on the modification of the combustor configuration in an effort to lower the NO_x concentrations in the exhaust gases. Specifically, the combustor will be staged and the optimum location of the secondary air insertion will be investigated.

Sincerely,

Ben T. Zinn

BTZ/jj

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1. Combustion Engineering, INC: "Combustion, Fossil Power Systems," edited by Singer, J. G., 1981, 3rd ed, Ch 17.

2. Severyanin, V. S.: "Application of Pulsating Combustion in Industrial Installations," in Proc. of the Symposium on Pulse-Combustion Applications, Battelle-Columbus Laboratories, 1982, pp. 7.1-7.23.

3. Bailie, R. C.: "Energy Conversion Engineering," Addison-Wesley Publishing Company, 1978, pp. 456-467.

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5. Martin, G . B. and Bowen, J. S.: "Control of Nitrogen Oxides from Combustion," Proc. of 3rd Interagency Conference on Energy and the Environment, Washington, D. C., June 1978, pp. 291-312.

6. Whitaker, R., McElroy, M., and Miller, M.: "Trade-offs in NO_x Control," EPRI Journal, January/February 1982, pp. 18-25.

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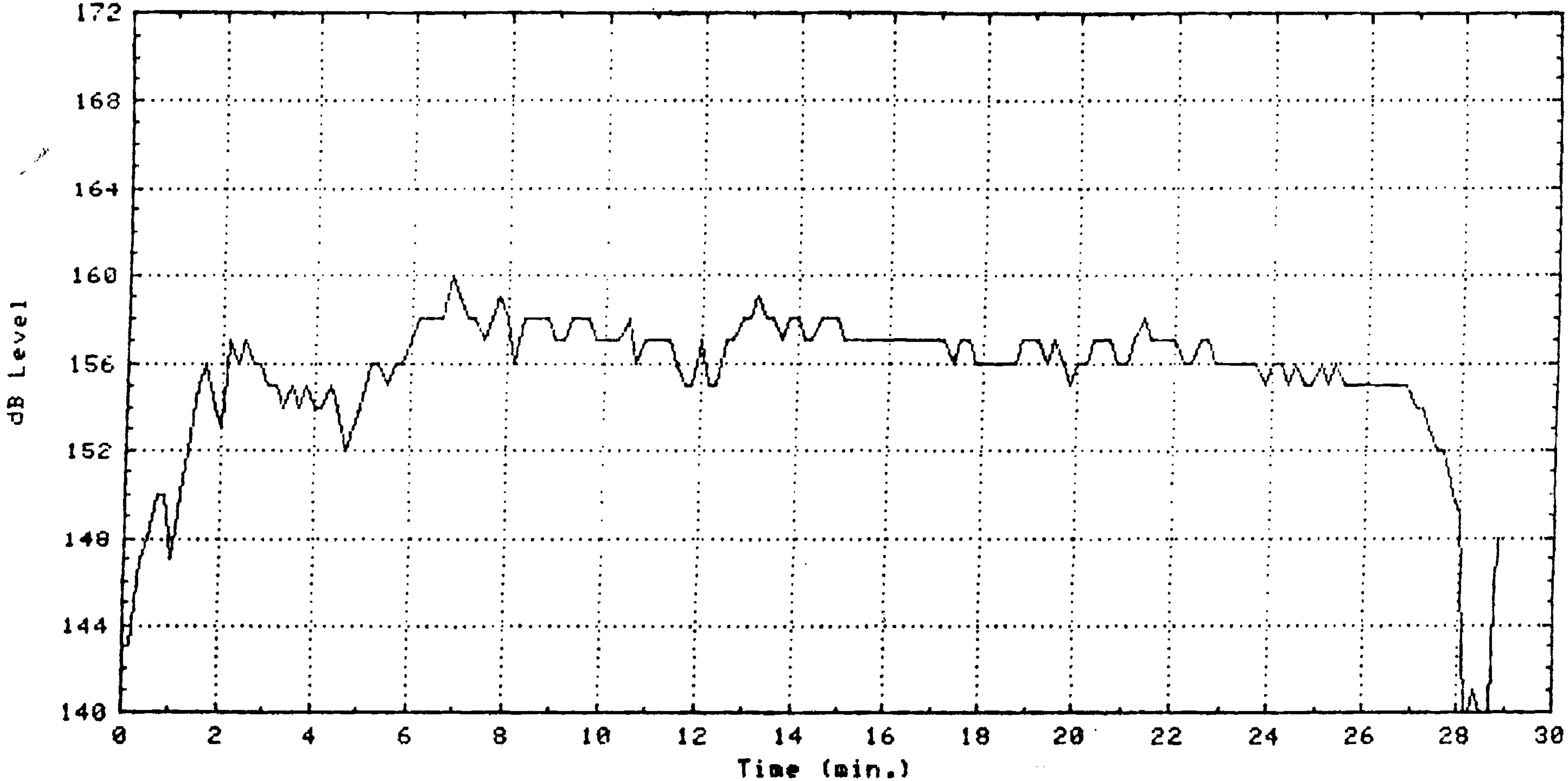


Fig. 1 : Time Variation of the dB Level of Oscillations (m_F = 37.3 gr/min, Alpha = 1.13)

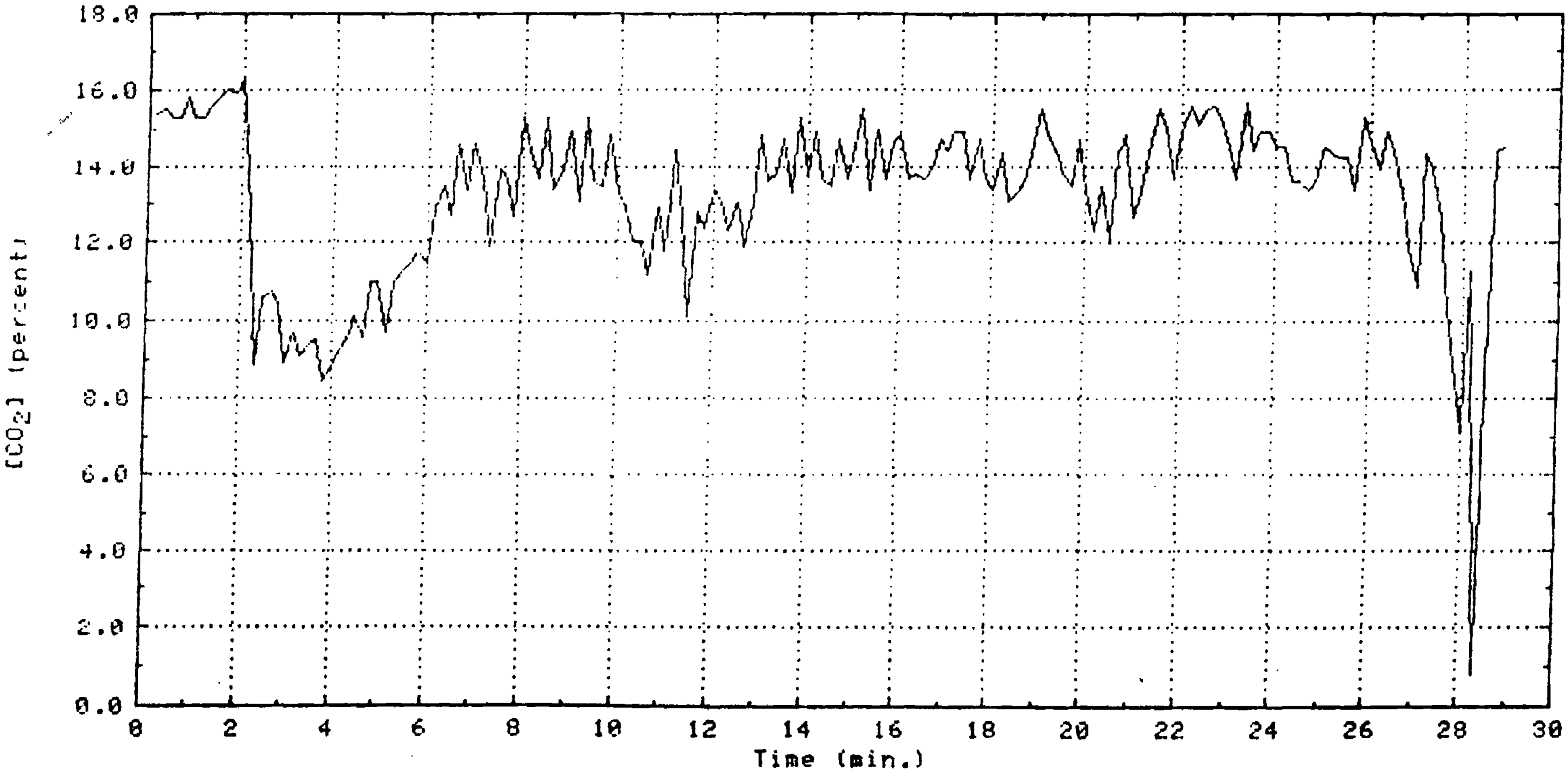


Fig. 2: Time Variation of the CO_2 Concentration (m_F = 37.3 gr/min, Alpha = 1.13)

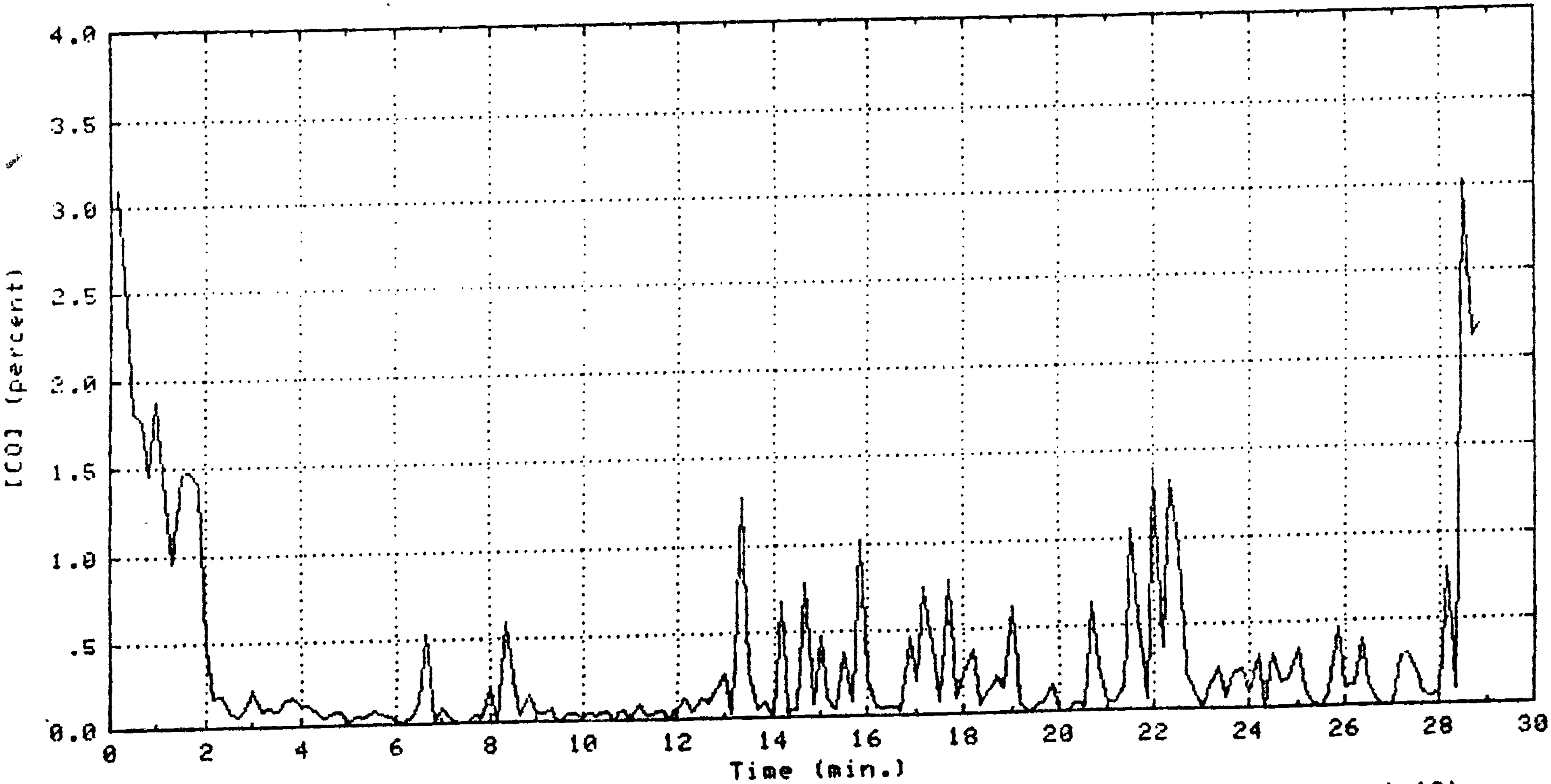


Fig. 3: Time Variation of the CO Concentration (m_F = 37.3 gr/min, Alpha = 1.13)

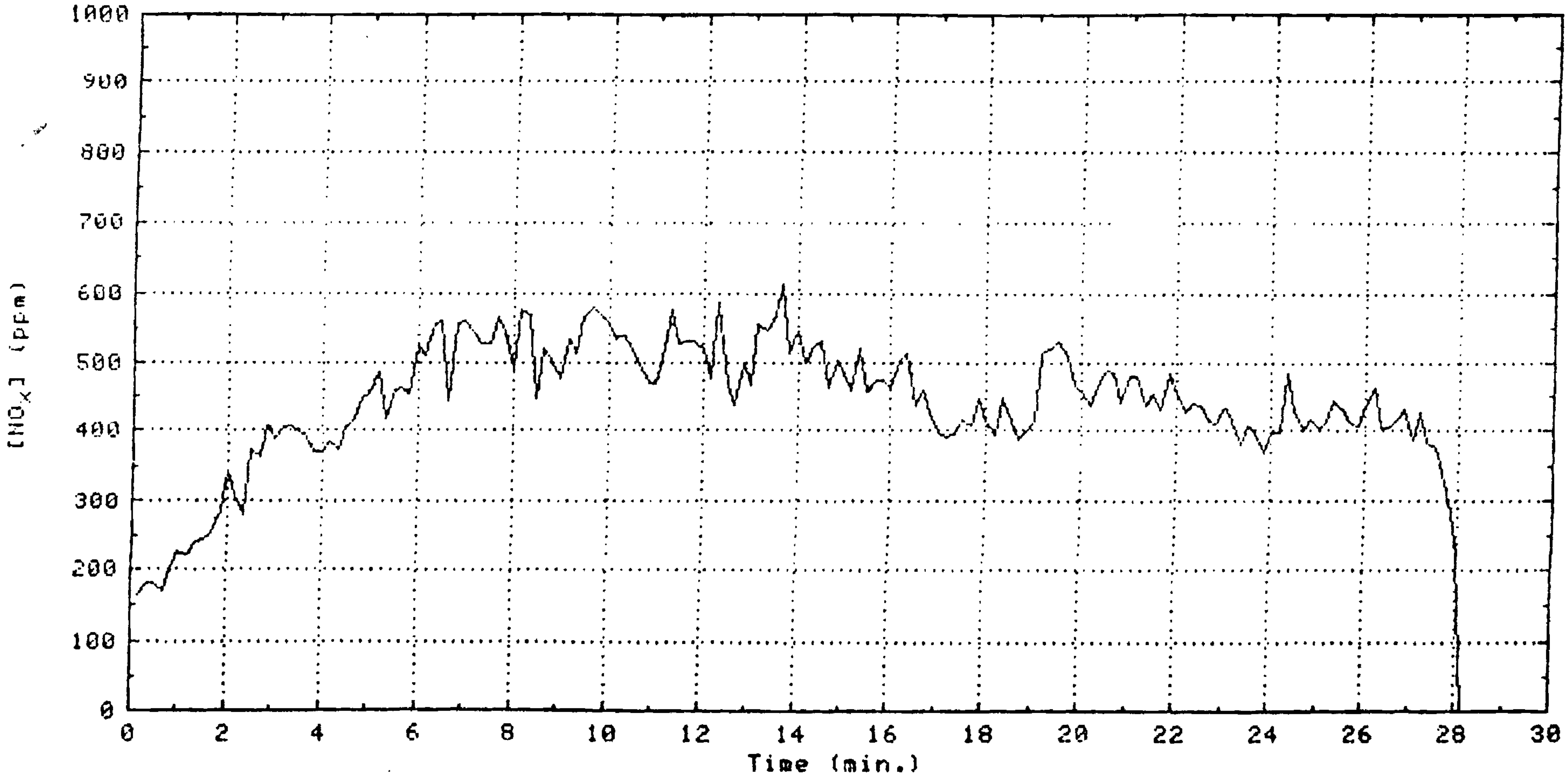


Fig. 4: Time Variation of the NO_x Concentration (m_F = 37.3 gr/min, Alpha = 1.13)

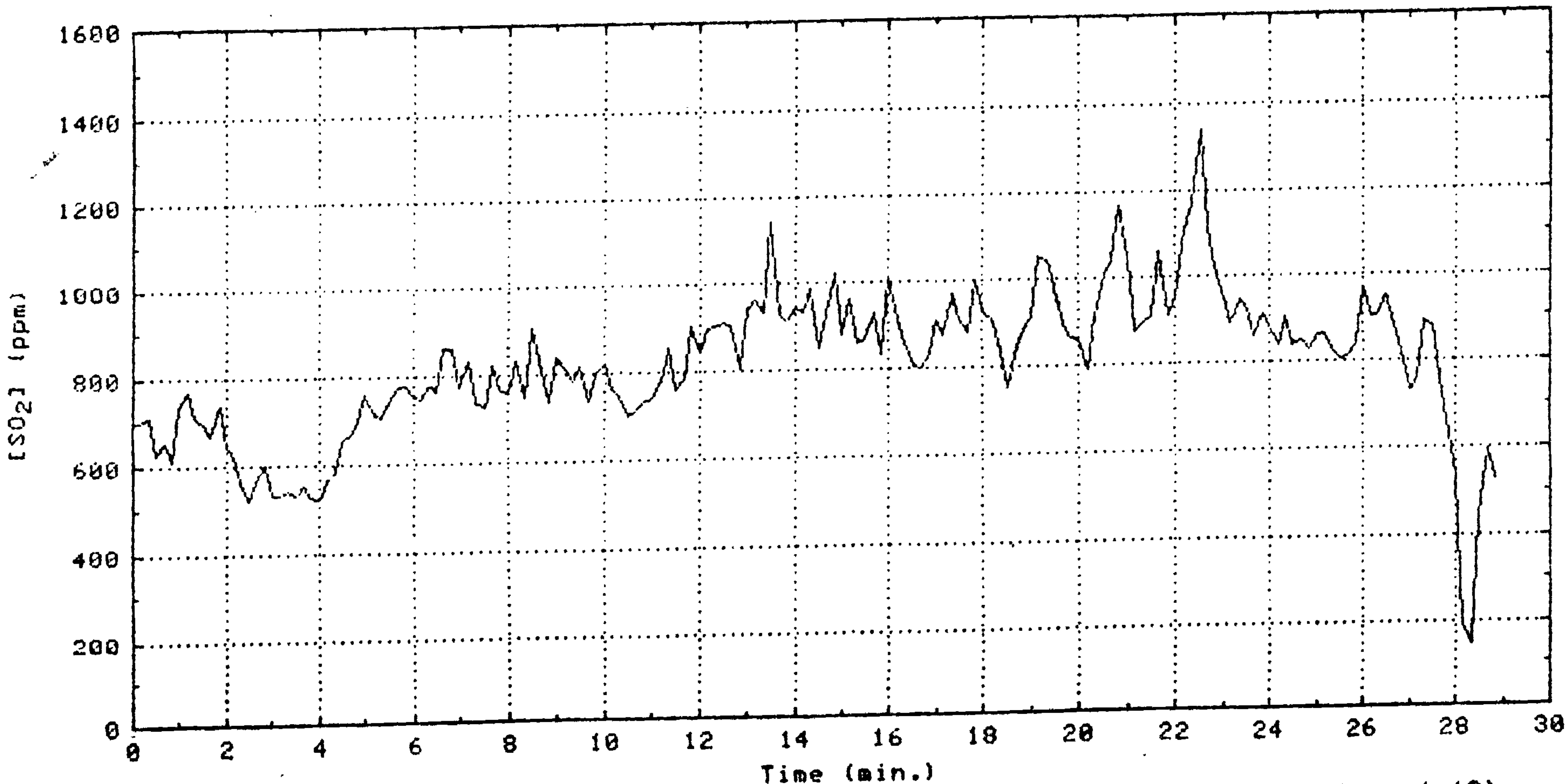


Fig. 5.: Time Variation of the SO_2 Concentration (m_F = 37.3 gr/min, Alpha = 1.13)

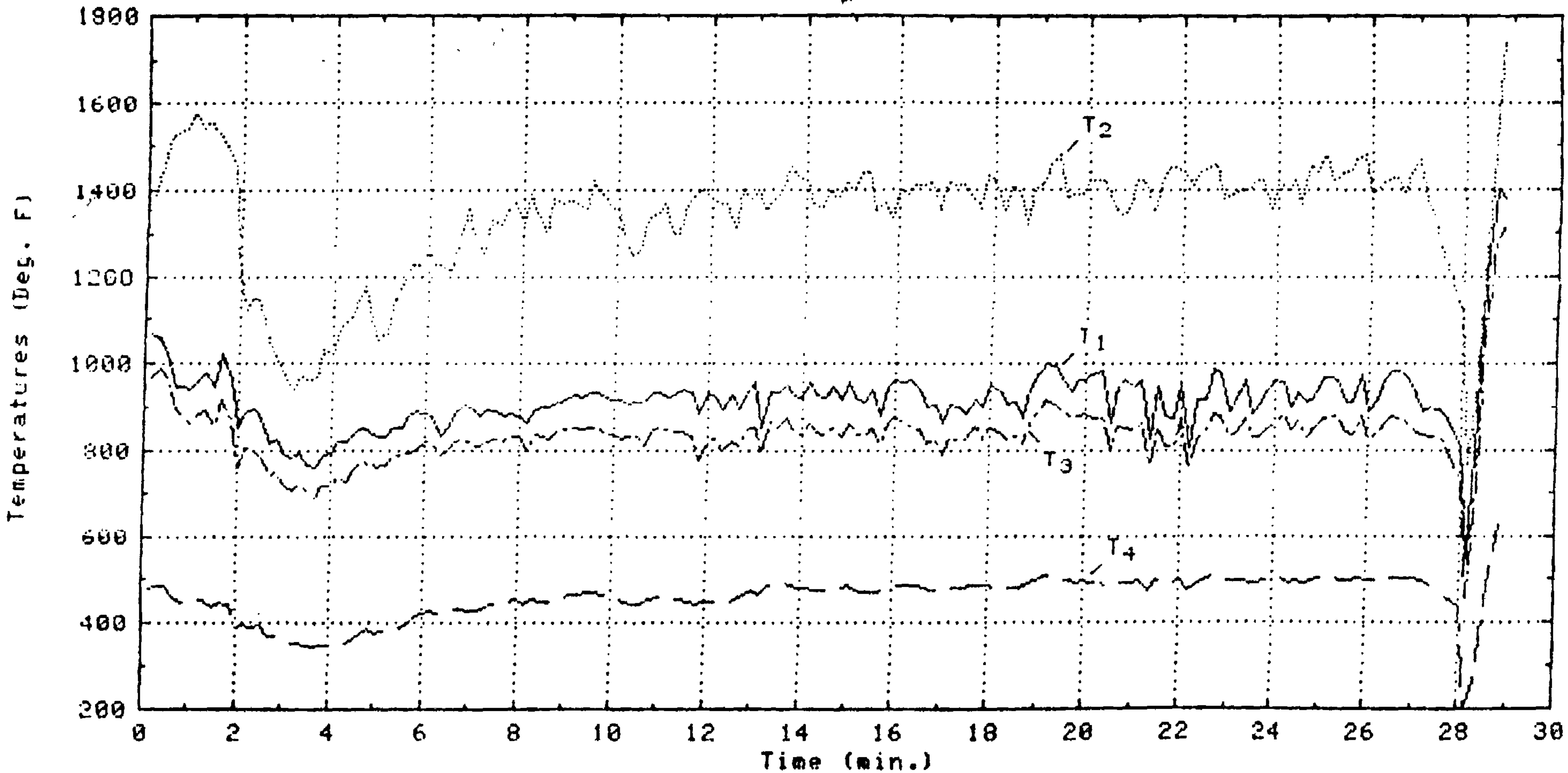


Fig. 6: Time Variation of Temperatures (m_F = 37.3 gr/min, Alpha = 1.13)

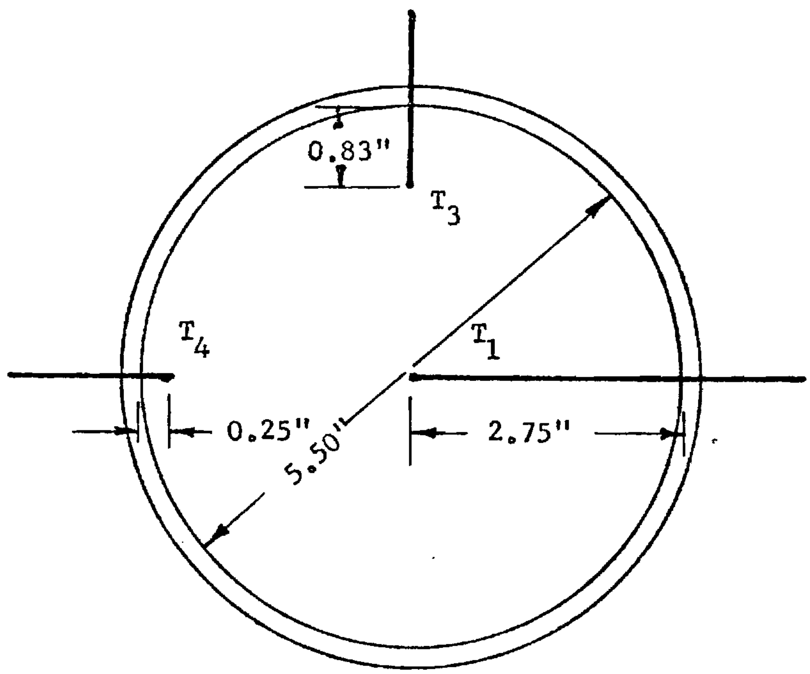


Figure 7. Locations of Thermocouples T_1, T_3, and T_4.

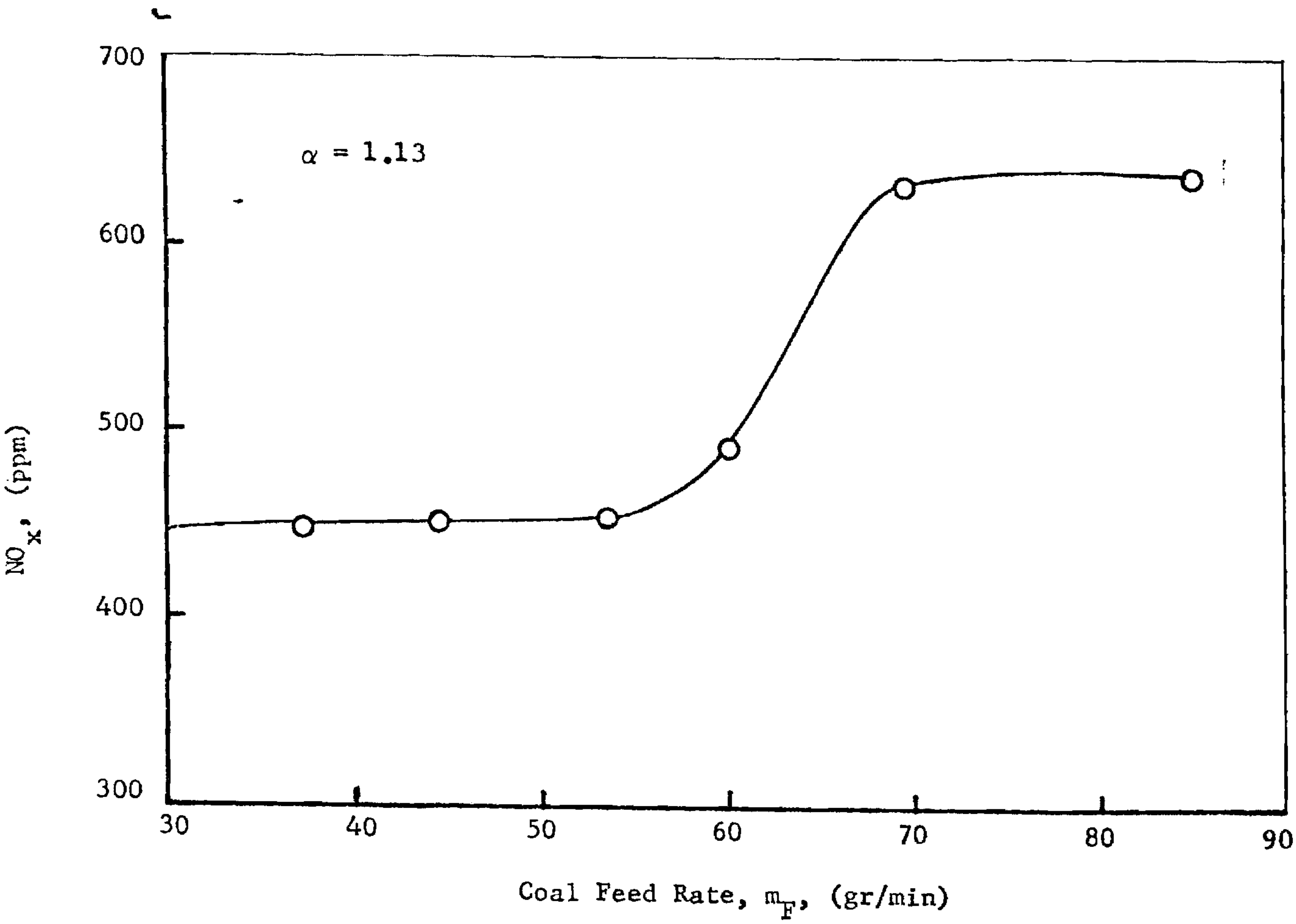


Figure 8. Dependence of the Exhaust Gas Average NO_x Concentrations on the Coal Feed Rate.

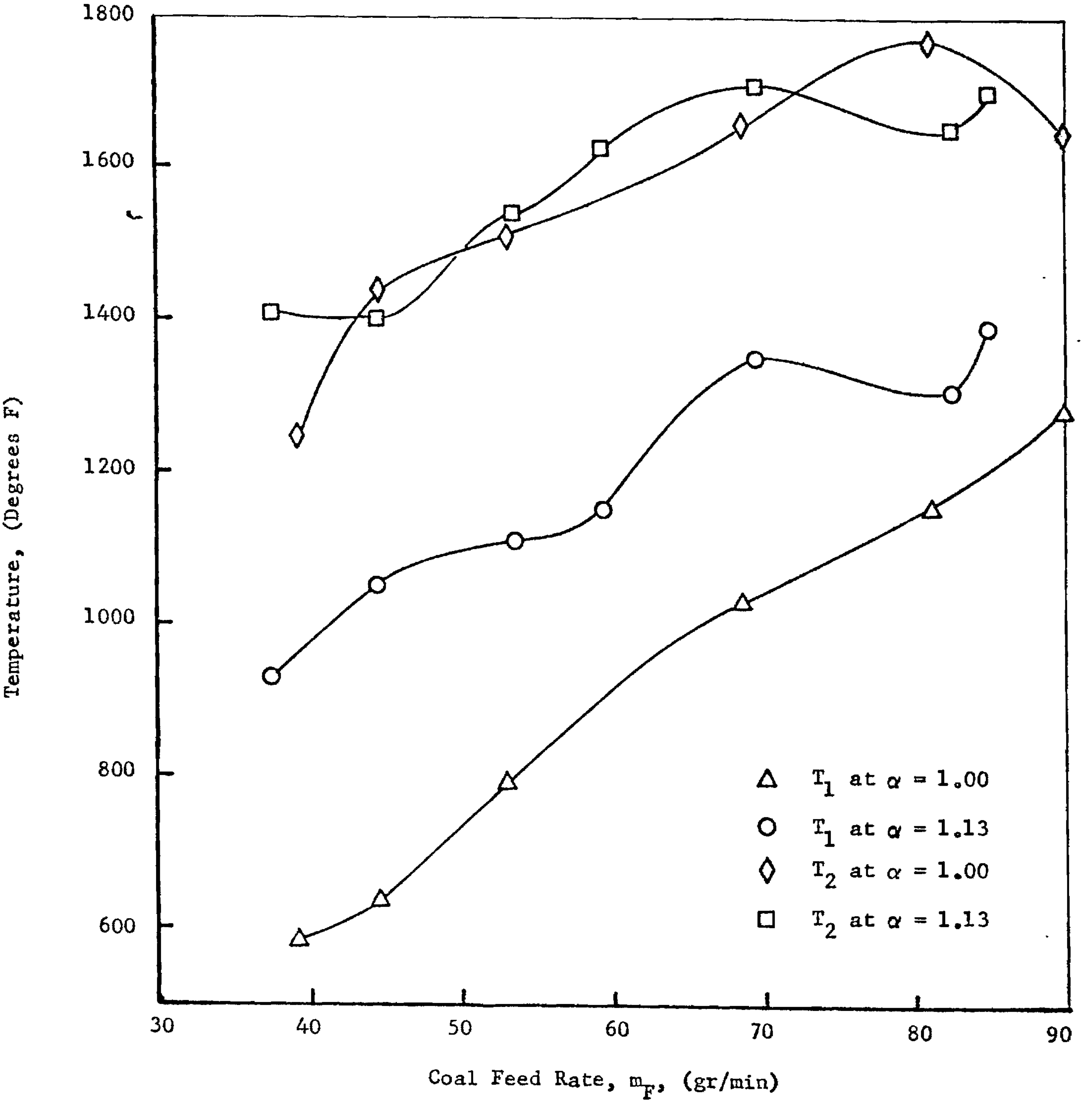


Figure 9. Exhaust Temperature 1 Foot above the Combustion Bed and 1 Foot below the Exhaust End of the Combustor as Functions of the Coal Feed Rate.

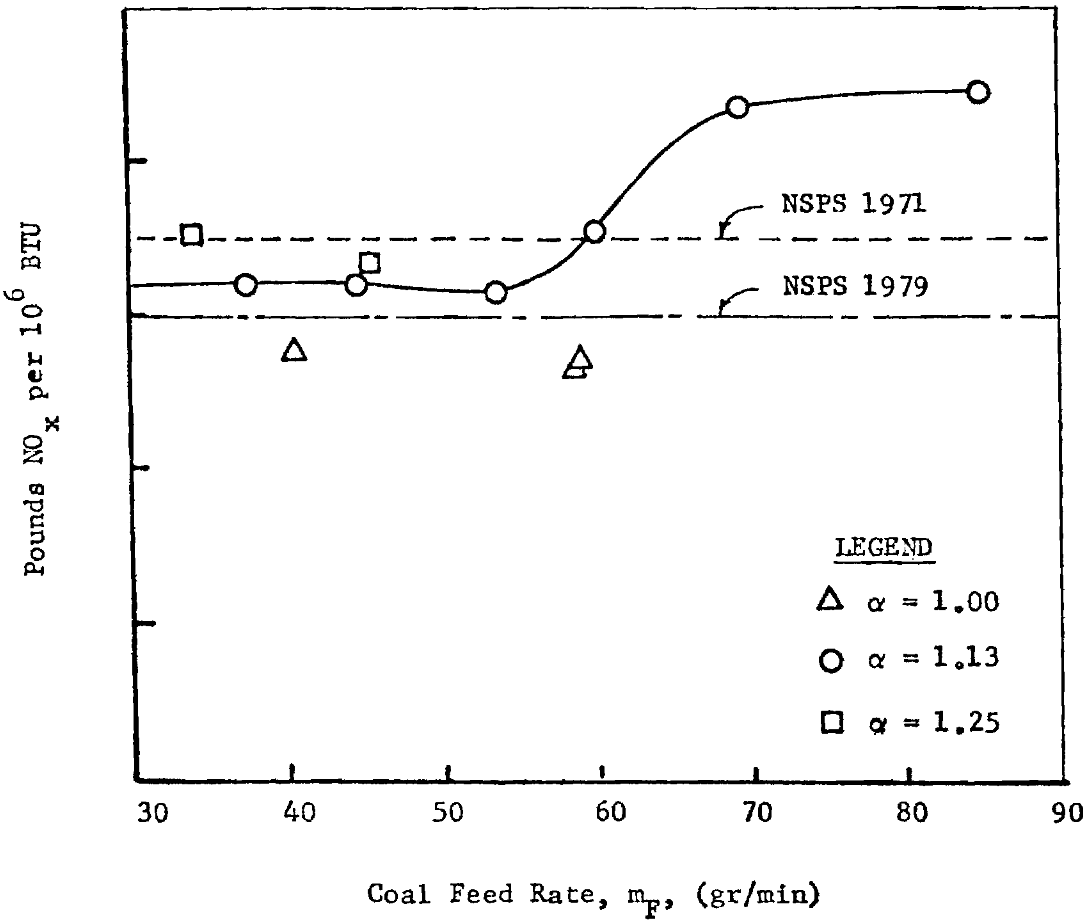


Figure 10. Dependence of the Pounds of Generated NO_x per 10^6 BTU of Heat Released upon the Coal Feed Rate.

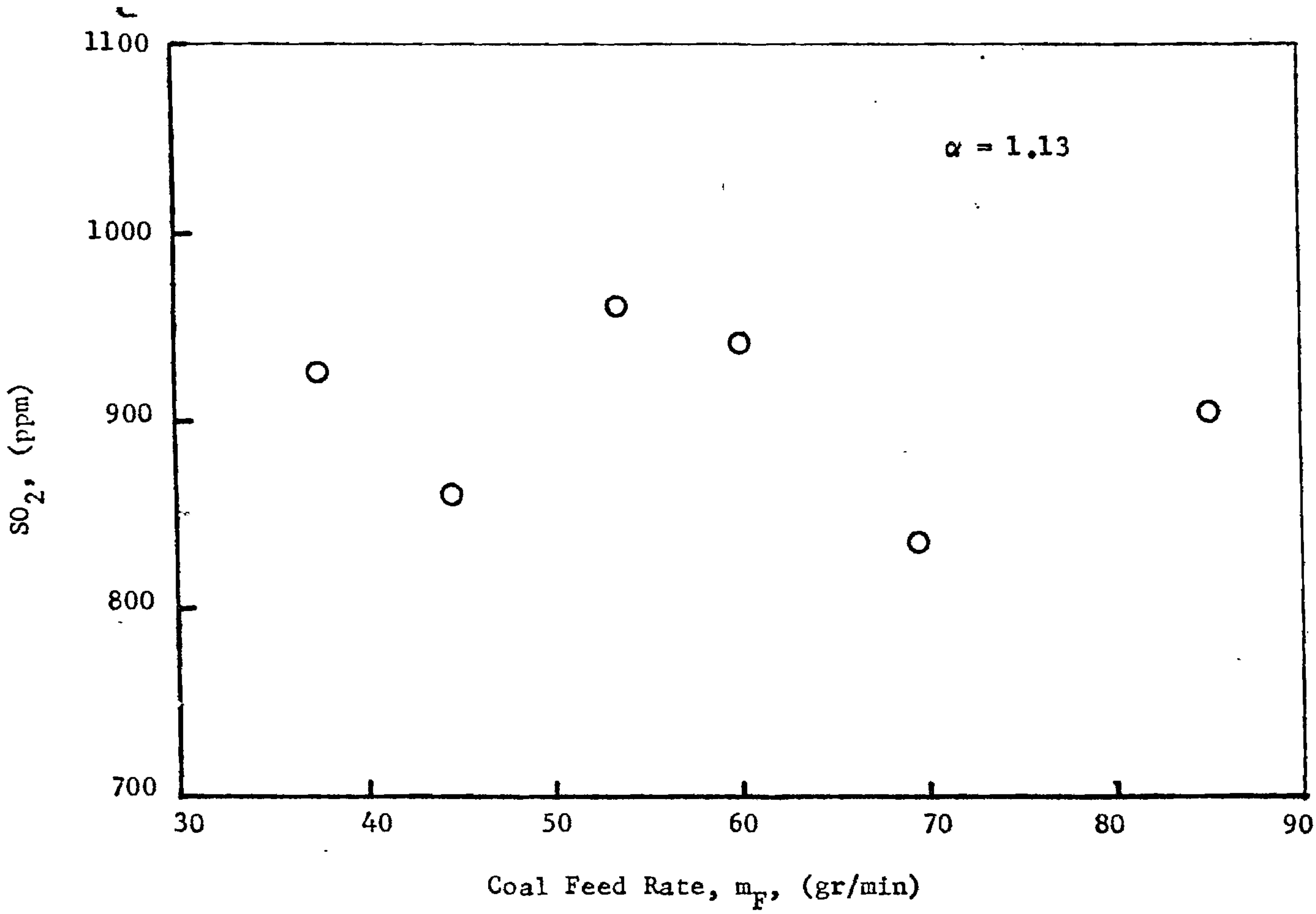


Figure 11. Dependence of the Exhaust Gas Average SO_2 Concentration on the Coal Feed Rate.

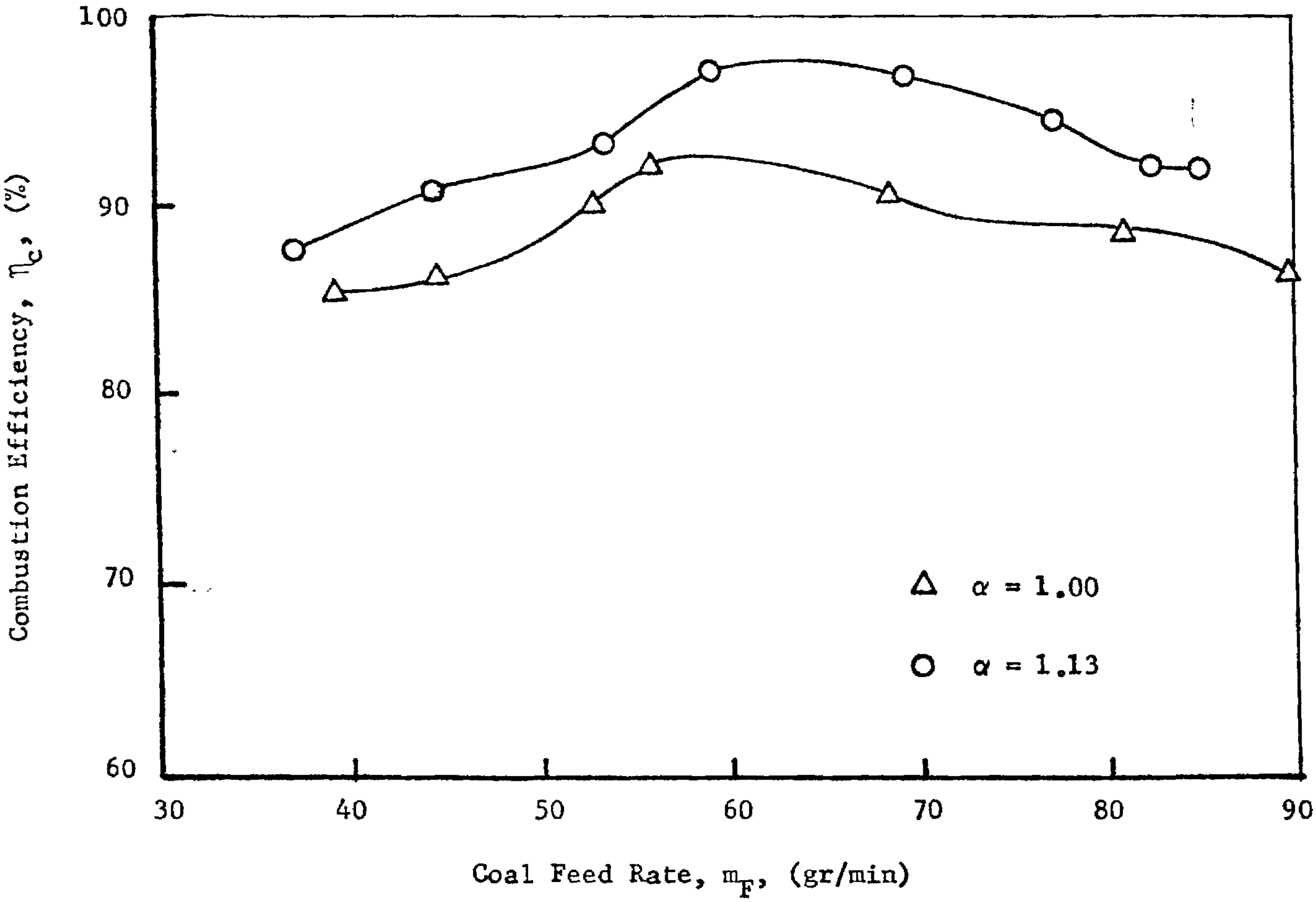


Figure 12. Dependence of the Average Combustion Efficiency on the the Coal Feed Rate.

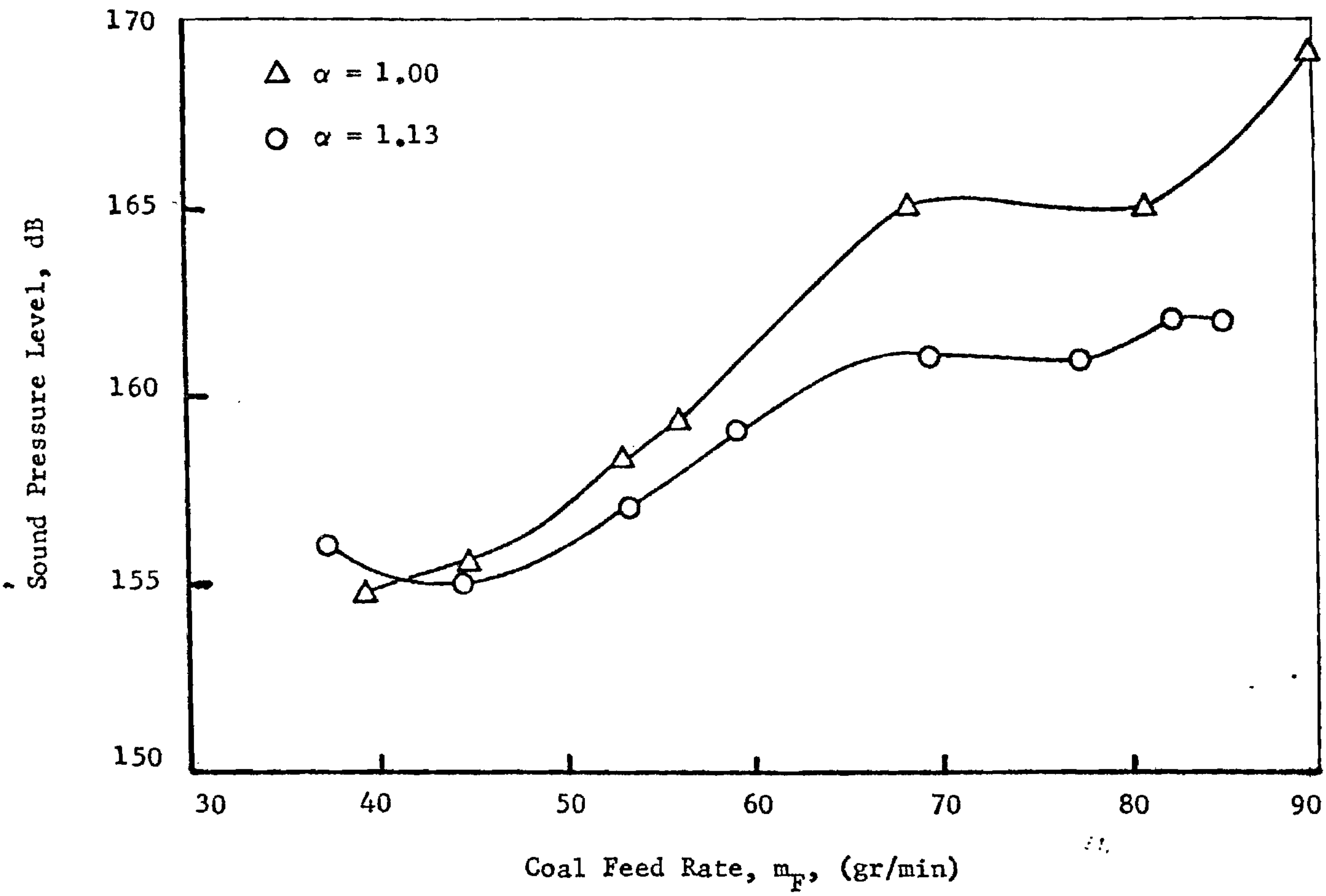


Figure 13. Dependence of the Average Sound Pressure Level of the Pulsations on Coal Feed Rate.

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF AEROSPACE ENGINEERING
ATLANTA, GEORGIA 30332
Telephone 404-894-3033 3000
Telex: SY2507 GTRI OCA ATL

Ben T. Zinn
Regents Professor
Daniel Guggenheim
School of Aeronautics

April 28, 1983

Mr. Jim Hickerson
Mail Stop 920-208
Pittsburgh Energy Technology Center
Pittsburgh, PA 15236

Subject: Technical Progress Report for the period January 1, 1983 through March 31, 1983 for work conducted under Contract No. DE-FG22-82 PC50257

Dear Mr. Hickerson:

This progress report describes the activities conducted under DOE Contract No. DE-FG22-82PC 50257 which supports a research program entitled "Development of a Coal Burning Pulsating Combustor for Power Generation". The period covered by the report extends from January 1, 1983 to March 31, 1983.

During this period a new combustor section and a water cooled feed mechanism was installed in the pulsating combustor. The new combustor section has a cam driven automatic shaker mechanism which periodically shakes the coal support grate. This action disturbs the bed and helps the accumulated ash to pass through the grate into the ash collector located in the lower decoupling chamber. The shaker mechanism was incorporated into the design of the combustor section to determine if mechanically shaking the bed would be effective in reducing the bed accumulation caused by agglomeration and caking that is characteristic of bituminous coals.

Tests using bituminous coals indicate that the shaker mechanism effectively controls the ash accumulation and reduces agglomeration. The periodic horizontal shaking motion of the bed also keeps the coal distribution in the bed more uniform.

Which, coupled with the pulsating acoustic motion of the combustion air provides more favorable conditions for improved mixing of the fuel and air in the combustion zone.

In addition, the orientation of the coal feed mechanism has been modified as shown in Figure 1. The feed chute has been eliminated and the auger has been designed to feed directly into the combustor. This configuration distributes the coal more uniformly on the combustor bed and reduces the possibility of a char buildup in the combustion bed.

The coal feed system has also been modified for water cooling. In previous tests at coal feed rates greater than 70 g/min. the increased combustor temperature in the area of the coal feed mechanism caused the coal at the exit plane of the coal feed chute to cake and adhere to the chute wall which restricted the feeding of the coal. The installation of a water jacket around the feed auger at the intersection with the combustor wall has resolved this problem and extended the operating limits of the combustor at the higher feed rates.

Tests were conducted during this reporting period using a ground coal which was sized to pass through a one-quarter inch mesh. The results of these tests indicate that the operation of the combustor using the finer ground coal was completely satisfactory. There was no evidence of agglomeration, caking or accumulation of char in the bed. However, the combustion efficiency using the finer coal was somewhat less than the combustion efficiency obtained using coal sized between one-quarter and one-half inch. The decrease in combustion efficiency using the finer ground coal was due, in part at least, to the elutriation of unburned fines. It is believed that operations at a higher combustor temperature, (i.e. with an insulated combustor) will allow a more complete burning of the coal fines and improve the combustion efficiency.

Tests were also conducted to determine the effects of swirl flow and higher frequency sound waves on the operating characteristics of the combustor. For these tests the combustion air was injected into the tube through a swirl type acoustic sound generator which introduced a swirling motion and high frequency (1800 to 2400 Hz) acoustic waves into the flow. Tests with the swirl/sound generator reduced the amplitude of the normal longitudinal pulsations in the tube by approximately two decibels and there was no evidence that tangential acoustic wave motion was established in the combustion zone. However, swirling flow was observed in the combustion zone and and the normal flame pattern was slightly altered. There was no evidence of appreciable change in combustion efficiency or NO_x concentration as a result of introducing swirl flow and higher frequency sound waves into the combustor flow.

Current research efforts on this program are concerned with establishing the combustion characteristics of a subbituminous coal in the pulsating combustor. Specifically, the purpose of these tests is to determine the effects of a non-agglomerating and non-caking coal on bed char and ash accumulation, and turndown ratio. This investigation should provide data that is needed to determine the operating limitations on the ranks of coal that are most suitable for use in the pulsating combustor.

A concurrent investigation is also in progress to determine the optimum secondary air injection location and orientation configuration for staged combustion. This work is a part of the continuing effort to reduce the NO_x formation and further improve the combustion efficiency of the developed pulsating combustor.

The research to be conducted during the next reporting period will be concerned with completing the investigation of the combustion characteristics of a subbituminous coal and determining the optimum secondary air injection location and orientation configuration. To assure sufficient time to accomplish these tasks, a request for a four to six weeks no-cost extension of this contract has been recently submitted.

Sincerely,

for Ben T. Zinn

BTZ/rk

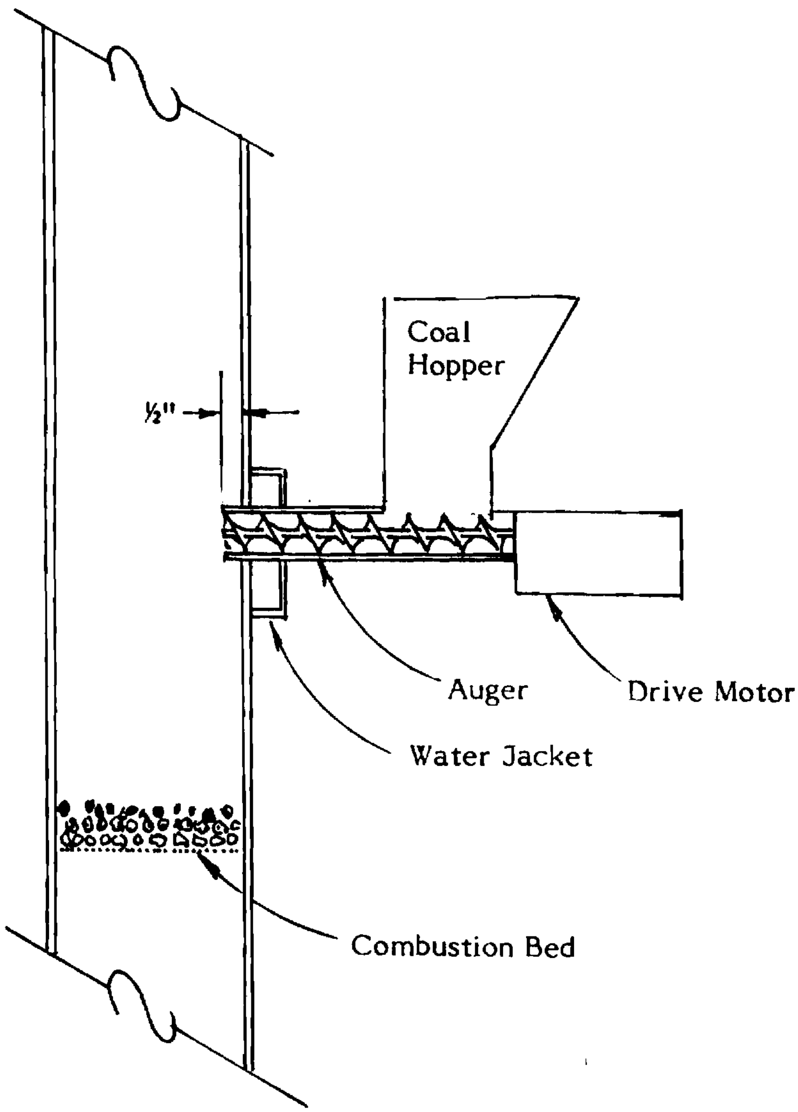


Figure 1. Schematic of Orientation of Coal Feed Mechanism.

F16-682

Page

DE-FG22-82PC50257	Development of a Coal Burning Pulsating Combustor

Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332

June 22, 1982

Completion Date: June 21, 1983

7. FY	8. Months or Quarters	J	A	S	O	N	D	J	F	M	A	M	J
83													

9. Cost Status a. Dollars Expressed in: Ten Thousand

b. Dollar Scale

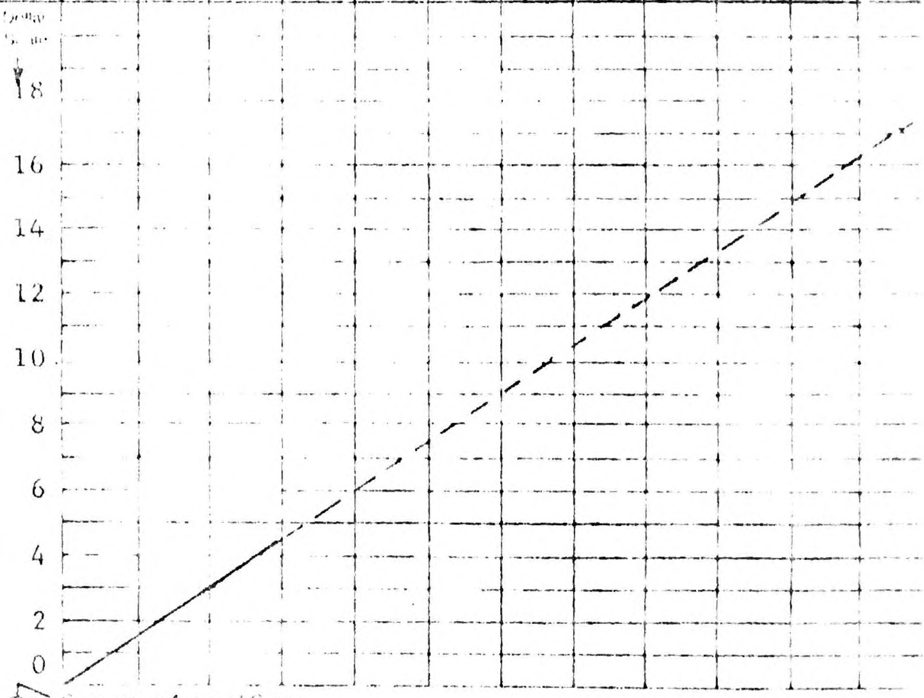
c. Cost Chart

Fund Source		1st	2nd	3rd	4th	Cum to Date	Tot Plan
DOE	P	4.4	4.4	4.4	4.3	4.4	17.5
	A	4.4					
	P						
	A						
	P						
	A						
	P						
	A						
Total P		4.4					
Total A		4.4					
Variance		0					

P = Planned A = Actual

Total Planned Costs for Program/Project

$ 175,507



c. Cumulative Accrued Costs

	J	A	S	O	N	D	J	F	M	A	M	J
Planned	1.[illegible]	2.9	4.4	5.9	7.3	8.8	10.2	11.7	13.2	14.6	16.1	17.[illegible]
Actual	[illegible]	[illegible]	[illegible]									
Variance	0	0	0									

Major Milestone Status

	Units Planned / Units Complete
Development of Computer Based Data System	P
	C
Modification of Sampling System to include NO, SO_2	P
	C
Design and Fabrication of [illegible] Combustor	P
	C
Development of Velocity [illegible] Capabilities	P
	C
[illegible] Bituminous Coal Tests	P
	C
[illegible] Coal Tests	P
	C
Report Preparation	P
	C

Project Manager / Representative and Date

RM EIA-459E

U.S. DEPARTMENT OF ENERGY

FEDERAL ASSISTANCE MANAGEMENT SUMMARY REPORT

FORM APPROVED
OMB No. 1900-0127

Page ____ of ____

1. Program/Project Identification No.: DE-FG22-82PC50257

2. Program/Project Title: Development of a Coal Burning Pulsating Combustor

3. Reporting Period: 10/1/82 through 12/31/82

4. Name and Address:
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332

5. Program/Project Start Date: June 22, 1982

6. Completion Date: June 21, 1983

7. FY: 83

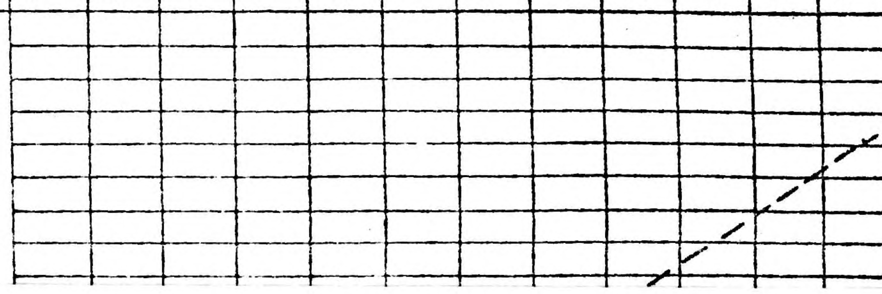
8. Months or Quarters: J A S O N D J F M A M J

9. Cost Status a. Dollars Expressed in: Ten Thousand

b. Dollar Scale: 18, 16, 14

10. Cost Chart

Quarter				Cum to	Tot



[X] None

9. Open Items

[X] None

10. Status Assessment and Forecast

[X] No Deviation from Plan is Expected

11. Description of Attachments

[X] None

12. Signature of Recipient and Date

Ben T. Zinn

13. Signature of DOE Reviewing Representative

FORM EIA 459E
(10/80)

U.S. DEPARTMENT OF ENERGY
FEDERAL ASSISTANCE MANAGEMENT SUMMARY REPORT

FORM APPROVED
OMB No. 1900-0127

Page ___ of ___

1. Program/Project Identification No.: DE-FG22-82PC50257

2. Program/Project Title: Development of a Coal Burning Pulsating Combustor

3. Reporting Period: 10/1/82 through 12/31/82

4. Name and Address:
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332

5. Program/Project Start Date: June 22, 1982

6. Completion Date: June 21, 1983

7. FY: 83

8. Months or Quarters: J A S O N D J F M A M J

9. Cost Status — a. Dollars Expressed in: Ten Thousand

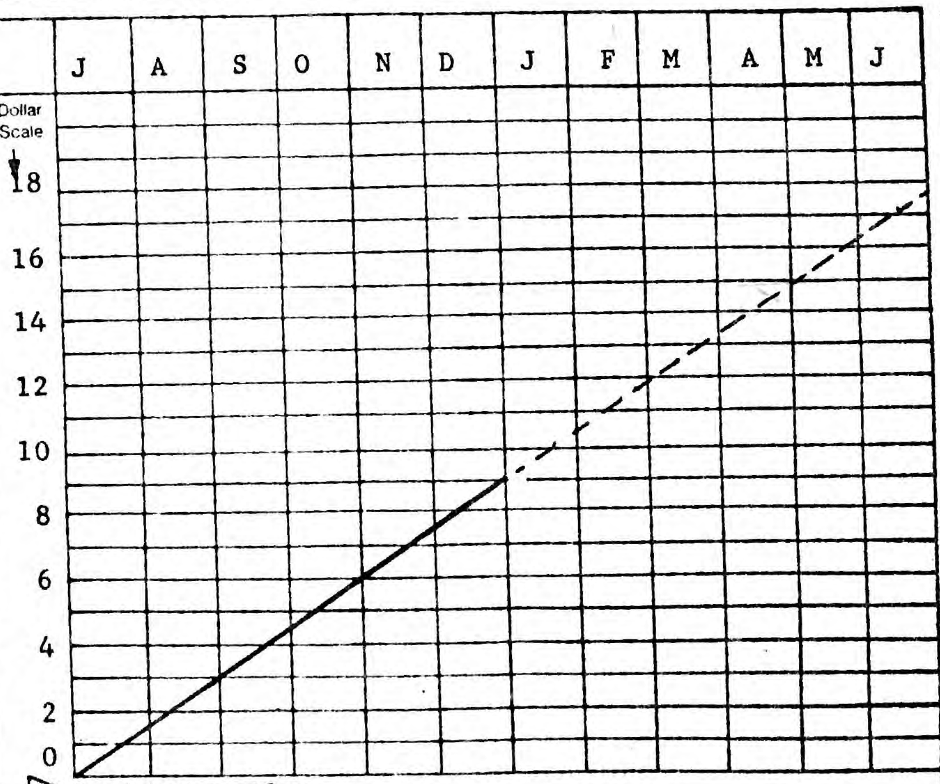
b. Dollar Scale

10. Cost Chart

Fund Source		1st	2nd	3rd	4th	Cum to Date	Tot Plan
DOE	P	4.4	4.4	4.4	4.3		17.5
	A	4.4	4.4				
	P						
	A						
	P						
	A						
	P						
	A						
Total P		4.4	8.8				
Total A		4.4	8.8				
Variance		0	0				

P = Planned A = Actual

Total Planned Costs for Program/Project: $ 175,407

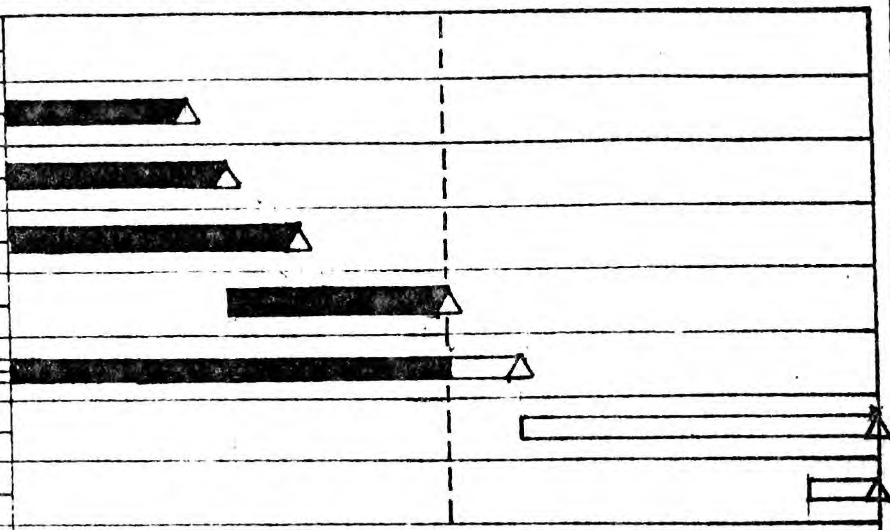


c. Cumulative Accrued Costs

	J	A	S	O	N	D	J	F	M	A	M	J
Planned	1.4	2.9	4.4	5.9	7.3	8.8	10.2	11.7	13.2	14.6	16.1	17.5
Actual	1.4	2.9	4.4	5.9	7.3	8.8						
Variance	0	0	0	0	0	0						

11. Major Milestone Status

Milestone	Units Planned / Units Complete
Development of Computer Based Data System	P / C
Modification of Sampling Train to Include NO_x SO_2	P / C
Design and Fabrication of an Optimized Combustor	P / C
Development of Velocity Measurement Capabilities	P / C
High Volatile Bituminous Coal Tests	P / C
Sub-Bituminous Coal Tests	P / C
Report Preparation	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C



12. Remarks

13. Signature of Recipient and Date: Ben T. Zinn '25/83

14. Signature of DOE Reviewing Representative and Date

FORM EIA 459E
(10-80)

U.S. DEPARTMENT OF ENERGY

FEDERAL ASSISTANCE MANAGEMENT SUMMARY REPORT

FORM APPROVED
OMB No. 1900-0127

Page ___ of ___

1. Program/Project Identification No.	2. Program/Project Title	3. Reporting Period
DE-FG22-82PC50257	Development of a Coal Burning Pulsating Combustor	1/1/83 through 3/31/83

4. Name and Address	5. Program/Project Start Date / 6. Completion Date
Georgia Tech Research Institute Georgia Institute of Technology Atlanta, Georgia 30332	5. June 22, 1982 6. June 21, 1983

7. FY: 83

8. Months or Quarters: J A S O N D J F M A M J

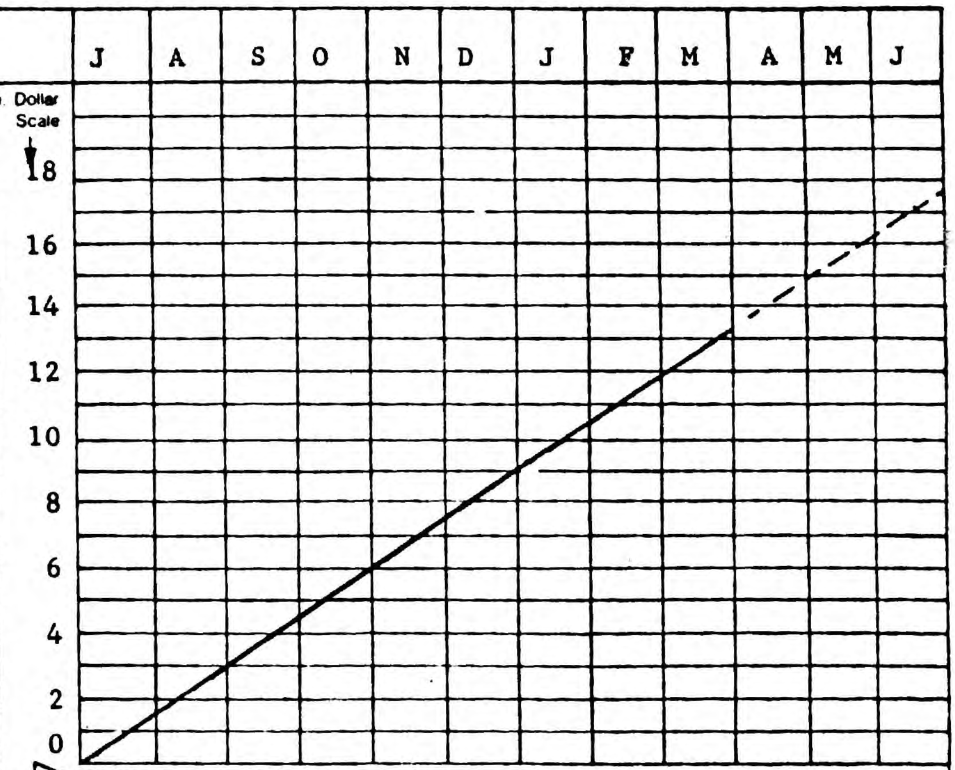
9. Cost Status — a. Dollars Expressed in: Ten Thousand — b. Dollar Scale

10. Cost Chart

Fund Source		Quarter 1st	2nd	3rd	4th	Cum to Date	Tot Plan
DOE	P	4.4	4.4	4.4	4.3		17.5
	A	4.4					
	P						
	A						
	P						
	A						
	P						
	A						
Total P		4.4	8.8	13.2			
Total A		4.4	8.8	13.2			
Variance		0	0	0			

P = Planned A = Actual

Total Planned Costs for Program/Project: $ 175,407

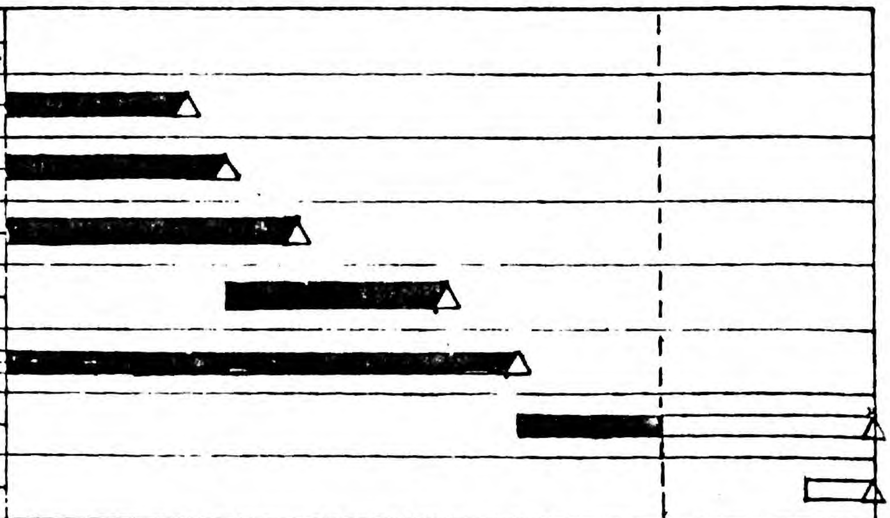


c. Cumulative Accrued Costs

	J	A	S	O	N	D	J	F	M	A	M	J
Planned	1.4	2.9	4.4	5.9	7.3	8.8	10.2	11.7	13.2	14.6	16.1	17.5
Actual	1.4	2.9	4.4	5.9	7.3	8.8	10.2	11.7	13.2			
Variance	0	0	0	0	0	0	0	0	0			

11. Major Milestone Status — Units Planned / Units Complete

Milestone	
Development of Computer Based Data System	P / C
Modification of Sampling Train to Include NO_x SO_2	P / C
Design and Fabrication of an Optimized Combustor	P / C
Development of Velocity Measurement Capabilities	P / C
High Volatile Bituminous Coal Tests	P / C
Sub-Bituminous Coal Tests	P / C
Report Preparation	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C
	P / C



12. Remarks

13. Signature of Recipient and Date: Ben T. Zinn 4/25/83

14. Signature of DOE Reviewing Representative and Date

FORM EIA 459F (10/80)

U.S. DEPARTMENT OF ENERGY

FEDERAL ASSISTANCE PROGRAM/PROJECT STATUS REPORT

FORM APPROVED OMB No. 1900-0127

1. Program/Project Identification No.	2. Program/Project Title	3. Reporting Period
DE-FG22-82PC50257	Development of a Coal Burning Pulsating Combustor	10/1/82 through 12/31/82

4. Name and Address

Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia 30332

5. Program/Project Start Date: June 22, 1982

6. Completion Date: June 21, 1983

7. Approach Changes

[X] None

8. Performance Variances, Accomplishments, or Problems

[X] None

9. Open Items

[X] None

10. Status Assessment and Forecast

[X] No Deviation from Plan is Expected

11. Description of Attachments

[X] None

12. Signature of Recipient and Date

Ben T. Zinn 1/25/83

13. Signature of DOE Reviewing Representative and Date

FINANCIAL STATUS REPORT

(Follow instructions on the back)

1. FEDERAL AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH REPORT IS SUBMITTED: Department of Energy	2. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER: DE-FG22-82PC50257	OMB Approved No. 80–RO180	PAGE 1 OF 1 PAGES	
3. RECIPIENT ORGANIZATION (Name and complete address, including ZIP code): Georgia Tech Research Institute, Atlanta, Georgia 30332	4. EMPLOYER IDENTIFICATION NUMBER: 58-0603146	5. RECIPIENT ACCOUNT NUMBER OR IDENTIFYING NUMBER: E-16-682	6. FINAL REPORT: [ ] YES [X] NO	7. BASIS: [X] CASH [ ] ACCRUAL
	8. PROJECT/GRANT PERIOD (See instructions): FROM (Month, day, year) 06/22/82 TO (Month, day, year) 06/21/83	9. PERIOD COVERED BY THIS REPORT: FROM (Month, day, year) 01/01/83 TO (Month, day, year) 03/31/83		

10. STATUS OF FUNDS

PROGRAMS/FUNCTIONS/ACTIVITIES ►	(a)	(b)	(c)	(d)	(e)	(f)	TOTAL (g)
a. Net outlays previously reported	$ 95,862.75	$	$	$	$	$	$ 95,862.75
b. Total outlays this report period	41,999.43						41,999.43
c. *Less:* Program income credits	- 0 -						- 0 -
d. Net outlays this report period *(Line b minus line c)*	41,999.43						41,999.43
e. Net outlays to date *(Line a plus line d)*	137,862.18						137,862.18
f. *Less:* Non-Federal share of outlays	22,922.60						22,922.60
g. Total Federal share of outlays *(Line e minus line f)*	114,939.58						114,939.58
h. Total unliquidated obligations	26,427.24						26,427.24
i. *Less:* Non-Federal share of unliquidated obligations shown on line h	7,655.91						7.655.91
j. Federal share of unliquidated obligations	18,771.33						18,771.33
k. Total Federal share of outlays and unliquidated obligations	133,710.91						133,710.91
l. Total cumulative amount of Federal funds authorized	143,176.00						143,176.00
m. Unobligated balance of Federal funds	9,465.09						9,465.09

11. INDIRECT EXPENSE — a. TYPE OF RATE *(Place "X" in appropriate box)*: [ ] PROVISIONAL [X] PREDETERMINED [ ] FINAL [ ] FIXED

b. RATE	c. BASE	d. TOTAL AMOUNT	e. FEDERAL SHARE
47.2%	MTDC	$41,534.34	$32,103.71

12. REMARKS: *Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.*

13. CERTIFICATION

I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.

SIGNATURE OF AUTHORIZED CERTIFYING OFFICIAL

TYPED OR PRINTED NAME AND TITLE: Sybil P. Small, Assistant Manager, Grants and Contracts Accounting

DATE REPORT SUBMITTED: April 29, 1983

TELEPHONE *(Area code, number and extension)*: (404) 894-4624

U.S. DEPARTMENT OF ENERGY
FEDERAL ASSISTANCE PROGRAM/PROJECT STATUS REPORT

M EIA 459F

FORM APPROVED
OMB No. 1900-0127

Program/Project Identification No. DE-FG22-82PC50257	2. Program/Project Title Development of a Coal Burning Pulsating Combustor	3. Reporting Period 1/1/83 through 3/31/83
Name and Address Georgia Tech Research Institute Georgia Institute of Technology Atlanta, Georgia 30332		5. Program/Project Start Date June 22, 1982 6. Completion Date June 21, 1983

Approach Changes

[X] None

8. Performance Variances, Accomplishments, or Problems

[X] None

9. Open Items

[X] None

0. Status Assessment and Forecast

[X] No Deviation from Plan is Expected

1. Description of Attachments

[X] None

Signature of Recipient and Date

Ben T. Zinn 4/25/83

13. Signature of DOE Reviewing Representative and Date

1. Program/Project Identification No.	2. Program/Project Title
DE-FG22-82PC50257	Development of a Coal Burning Pulsating Combustor for Industrial Power Generation

3. Performer (Name, Address)	4. Program/Project Start Date	5. Program/Project Completion Date
Georgia Tech Research Institute Georgia Institute of Technology, Atlanta, Georgia 30332	June 22, 1982	June 21, 1983

6. Identification Number	7. Planning Category (Work Breakdown Structure Tasks)	8. Program/Project Duration: J	A	S	O	N	D	J	F	M	A	M	J	9. Comments (Notes, Name of Performer)
1	Development of Measurement Capabilities													
	Development of Computer Based Data System													
	Modification of Sampling Train to Include NO and SO_2													
	Design and Fabrication of an Optimized Combustor													
	Development of Velocity Measurement Capabilities													
2	Testing and Analysis													
	High Volatile Bituminous Coal													
	Sub-Bituminous Coal													
	Report Preparation													

10. Remarks

11. Signature of Recipient and Date	12. Signature of DOE Reviewing Representative and Date
Ben T. Zinn 10/4/82	

FEDERAL ASSISTANCE BUDGET INFORMATION FORM

FORM EIA 459C
(10-80)

FORM APPROVED
OMB No. 1900-0127

1. Program/Project Identification No.	2. Program/Project Title	
DE-FG22-82PC50257	Development of a Coal Burning Pulsating Combustor for Industrial Power Generation	
3. Name and Address: Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, Georgia 30332		4. Program/Project Start Date: 6/22/82
		5. Completion Date: 6/21/82

SECTION A - BUDGET SUMMARY

1.				143,176	$ 32,331	175,507
2.						
3.						
4.						
5. Totals				143,176	32,331	175,507

SECTION B - BUDGET CATEGORIES

6. Object Class Categories	(1)	(2)	(3)	(4)	Total (5)
a. Personnel	88,901	$		$	$ 88,901
b. Fringe Benefits	6,363				6,363
c. Travel	1,348				1,348
d. Equipment	15,620				15,620
e. Supplies	6,541				6,541
f. Contractual	-0-				-0-
g. Construction	-0-				-0-
h. Other	-0-				-0-
i. Total Direct Charges	118,673				118,673
j. Indirect Charges	56,734				56,734
k. TOTALS	$ 175,407	$	$	$	$ 175,407
7. Program Income	$	$	$		$

U S DEPARTMENT OF ENERGY

NOTICE OF ENERGY RD&D PROJECT

RM DOE 538
78)

PROVED FOR USE BY
ITHSONIAN SCIENCE INFORMATION EXCHANGE

FORM APPROVED
OMB NO 38 R 0190

1 DESCRIPTIVE TITLE OF WORK

Development of a Coal Burning Pulsating Combustor for Industrial Power Generation

2 PERFORMING ORGANIZATION CONTROL NUMBER

E-16-682

3 CONTRACT GRANT OR PURCHASE ORDER NUMBER

DE-FG22-82PC50257

4 CONTRACTOR'S PRINCIPAL INVESTIGATOR/PROJECT MANAGER AND ADDRESS WHERE WORK IS PERFORMED

a NAME (Last First, MI) Dr. Ben T. Zinn, School of Aerospace Engineering PHONE (404) 894-3033

b BUSINESS ADDRESS STREET Georgia Institute of Technology

CITY Atlanta STATE Georgia ZIP 30332

5. a NAME OF PERFORMING ORGANIZATION

Georgia Institute of Technology (Organization)

School of Aerospace Engineering (Department)

b MAILING ADDRESS (If Different From 4B) same as above

c TYPE OF ORGANIZATION PERFORMING THE WORK (Enter applicable code from instructions). C U

6 SUPPORTING ORGANIZATION

a. DOE PROGRAM DIVISION OR OFFICE (Full Name) Pittsburgh Energy Technology Center
Acquisition and Assistance Division

b TECHNICAL MONITOR (Last, First, MI) Ritz, Harry

c ADDRESS (If Different from DOE Hqs) PETC Mail-Stop 920-208, Pittsburgh, PA 15236

d ADMINISTRATIVE MONITOR (Last First MI)

7 PROJECT SCHEDULE (a) START DATE June 22, 1982 (Month) (Year) (b) EXPECTED COMPLETION DATE June 21, 1983 (Month) (Year)

8 a FUNDING OPERATING AND CAPITAL EQUIPMENT OBLIGATION (In Thousands of Dollars)

FUNDING ORGANIZATION(S)		APPROXIMATE CUMULATIVE PRIOR FISCAL YEARS	CURRENT FY		
1 DOE		-0-	143		
2 Georgia Tech		-0-	32		
3					

b DOE BUDGETING AND REPORTING CLASSIFICATION CODE

9 DIRECT SCIENTIFIC AND TECHNICAL MANPOWER

	PROFESSIONAL	GRAD STUDENTS	OTHER	TOTAL
NUMBER	4	3	3	10
EQUIVALENT PERSONYEARS	.92 yrs	.83 yrs	.30yrs	2.05yrs

DETACH HERE BEFORE SUBMITTING

10. **SUMMARY OF WORK** *(Limit to 200 words or less - include a description, objective, approach and a final product expected.)*

Results of past pulsating combustion research indicate that properly designed pulsating combustors may possess high thermal and combustion efficiencies, high combustion intensities, high convective heat transfer rates, reduced pollutants formation and a capability for maintaining heat transfer surfaces clean. This study is concerned with the development of a coal burning pulsating combustor that will possess most or all of the above-mentioned advantages. The developed combustor is based upon the Rijke Tube principles. It consists of a vertical circular tube whose fundamental mode is excited by burning coal on a metal wire grid located at the middle of the lower half of the tube. The feasibility of burning coal efficiently under pulsating conditions in a Rijke type combustor has been demonstrated in research conducted under this program to date. The current program is concerned with the quantitative determination of the characteristics of the developed pulsating combustor. Specifically, the combustion efficiencies, the concentrations of particulates, NO_x, SO_2 and CO in the exhaust flow and the combustion intensity will be determined for different fuel feed rates, different equivalence ratios and different coal sizes and types. The measured data will be analyzed to determine the optimum range of operating conditions of the developed combustor.

11 PROGRESS SINCE LAST REPORT *(Limit to 100 words.)*

Since the renewal of this DOE contract, a Beckman model 951A NO/NO_x chemiluminescent analyzer and a Beckman model 865 SO_2 infrared analyzer were purchased and checked out. These instruments will be used to continuously measure the concentrations of NO_x and SO_2 in the pulsating combustor exhaust flow. The existing combined gas-particulates sampling train was completely modified to satisfy the new system requirements. Specifically, the previously utilized ice bath condenser separator was replaced by a Perma Pure dryer that uses the principle of permeation-distillation to extract the water from the sample in water vapor form, which is required for SO_2 concentration measurements. While the development of the new sampling train has been completed, the initiation of testing had to be postponed because of difficulties with purchased calibration gases (for the NO_x analyzer) whose actual compositions failed to comply with those claimed by their supplier.

12. List publications in the last year that are available to the public which have resulted from the product *(Please give a complete bibliographic citation. Use additional sheets if necessary.)*

See attached

13 GENERAL TECHNOLOGY CATEGORIES *(Enter applicable code or codes from instructions.)*

A1 F5

14. PHASE OF RD&D *(Enter Project Percentage in Applicable Boxes)*

a. 10% Basic Research
b. 10% Applied Research
c. 20% Technology Development
d. 50% Engineering Development
e. 10% Demonstration

15 KEYWORDS (Minimum of 5)

Combustion in Practical Systems
Coal Energy Conversion
Coal Pulsating Combustion

16 A. RESPONDENT'S NAME & ADDRESS
Ben T. Zinn, School of Aerospace Eng.
Georgia Institute of Technology
Atlanta, Ga. 30332

B PHONE NO
404 894 3033

C DATE
October 1, 1982

12.1 Ben T. Zinn, Brady R. Daniel, and T. S. Sheshadri: "Application of Pulsating Combustion in the Burning of Solid Fuels", Proceedings of the Symposium on Pulse Combustion Technology for Heating Applications, May 1980, p.p. 239-248.

12.2 B. T. Zinn, J. A. Carvalho, Jr., N. Miller, and B. R. Daniel: "Development of a Pulsating Combustor for Burning of Wood", Proceedings of the Symposium on Pulse-Combustion Applications, March 82, p.p. 11.01-11.11.

12.3 Ben T. Zinn, Nehemia Miller, Joao A. Carvalho, Jr., and Brady R. Daniel: "Pulsating Combustion of Coal in a Rijke Type Combustor", Nineteenth Symposium (International) on Combustion, Haifa, Israel, August 82. To be published in the volume of papers.

DOE FINAL REPORT

DOE/PC/50257- 4

DEVELOPMENT OF A COAL BURNING PULSATING COMBUSTOR FOR INDUSTRIAL POWER

By

Ben T. Zinn

Muh-Rong Wang

Brady R. Daniel

Prepared for

DEPARTMENT OF ENERGY

PITTSBURGH ENERGY TECHNOLOGY CENTER

Under

DOE Contract No. DE-FG22-82PC50257

November 1983

GEORGIA INSTITUTE OF TECHNOLOGY

A Unit of The University System of Georgia
School of Aerospace Engineering
Atlanta, Georgia 30332

Disclaimer

DOE FINAL REPORT

DOE/PC/50257- 4

DEVELOPMENT OF A COAL BURNING PULSATING COMBUSTOR FOR INDUSTRIAL POWER

Prepared for

Department of Energy

Pittsburgh Energy Technology Center

by

Ben T. Zinn

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Brady R. Daniel

School of Aerospace Engineering

Georgia Institute of Technology

Atlanta, Ga. 30332

DOE Contract No. DE-FG22-82PC 50257

November 1983

ABSTRACT

This report describes the results obtained during a twelve months period under DOE contract DE-FG22-82PC50257 which terminated on June 21, 1983. The research conducted under this program investigated the performance characteristics of a previously developed coal burning pulsating combustor whose design is based upon the Rijke tube principles. The combustor consists of a vertical tube opened at both ends with a fuel burning bed located in the middle of its lower half. Coal is supplied to the bed by a rotating auger-type feed system located 1 ft above the bed. Following ignition, the interaction between the combustion process and the combustor flow results in the excitation of high amplitude (up to 165 dB) fundamental, longitudinal acoustic mode oscillations with frequencies in the range 75-90 Hz in the combustor. Maximum amplitudes occurred near stoichiometric air/fuel ratio operation, suggesting that systems utilizing the developed combustor should possess high thermal efficiencies, as they could operate with relatively little excess air. Both bituminous and subbituminous coals with sizes in the range 1/4" - 1/2" were burned in the developed pulsating combustor. The CO, CO_2, NO_x, SO_2, O_2 and particulates concentrations in the exhaust flow were measured to evaluate the combustor performance. In tests with bituminous coal, combustion efficiencies higher than 95% for coal feed rates in the range 42-60 lb/ft^{2}hr were achieved with only 13% excess air while NO_x and SO_2 concentrations were comparable to those obtained with other steady state combustors. A higher performance was attained in initial tests with subbituminous coal. Finally, pulsating operation was possible under fuel rich conditions suggesting that the developed pulsating combustor could be possibly used as a gasifier.

I. INTRODUCTION

This report describes the results obtained under a research program entitled "Development of a Coal Burning Pulsating Combustor for Industrial Power" which was supported under DOE Contract No. DE-FG22-82PC50257 during the period June 27, 1982 to July 26, 1983. The research conducted under this program was concerned with the determination of the performance characteristics of a Rijke-type, coal (or any other solid fuel) burning pulsating combustor which had been developed earlier under this program[1,2].

As its name implies, the burning in a pulsating combustor takes place under oscillatory conditions. The excitation of acoustic velocity oscillations in the combustor is expected to enhance mixing processes which, in turn, intensify the combustion process. Keeping this in mind, the present study had been undertaken with the hope that the developed pulsating combustor would possess high thermal and combustion efficiencies, high combustion intensity and be capable of burning unpulverized coal. In addition, it had been expected that the developed combustor will exhibit improved convective heat transfer characteristics which are known[3] to occur when pulsations are present in a flow. Finally, it was of interest to determine whether benefits such as reduced slagging, ability to maintain heat transfer surfaces clean by the scrubbing action of the pulsating flow and reduced NO_x formation[4], which were observed in other pulsating combustors, would be also present in the developed pulsating combustor.

The reasons for expecting the above mentioned benefits are discussed in detail in Refs. 1 and 2 and, consequently, they are not to be repeated herein. Instead, this report discusses the results obtained in a series of tests in which the performance of the developed pulsating combustor under various operating conditions was investigated.

II. DEVELOPED EXPERIMENTAL SETUP

The developed combustor is based upon the principles of the acoustic Rijke Tube[5,6] which consists of a vertical pipe of length L containing a heated metal gauze at a distance L/4 from the bottom of the tube. The pipe is open at both ends and heat transfer from the gauze to the surrounding air results in an upward flow of air (due to buoyancy) and the excitation of the fundamental, longitudinal acosutic mode of the tube. The Rijke type, coal burning pulsating combustor developed under this program is shown in Fig. 1. A coal burning bed located at a distance of L/4 from the bottom of the tube serves as the Rijke tube heat source which excites the fundamental acoustic mode of the combustor whose wave structure is also shown in Fig. 1. The combustion bed is located in a region where both the acoustic pressure and velocity are nonzero and the interaction between these oscillations and the combustion process establishes a positive feedback loop which provides the energy required for maintaining the oscillations.

Coal is fed into the bed at a preselected rate by an auger-type feed system that is attached to the combustor wall just above the combustion bed. A preselected flow rate of combustion air enters the combustor through the bottom decoupling chamber. Combustion occurs when this air moves through the bed and reacts with the combustible volatiles and coal. The presence of acoustic velocity oscillations in the bed increases the coal burn rate by improving the efficiencies of the gas phase mixing processes and the transport of oxygen to the coal surface.[7,8,9]

Two auger-type feed systems have been developed under this program to date, see Fig. 2. The auger shown in the right of Fig. 2 was developed later on in the program after it had been found that the auger on the left of Fig. 2 produced an undersirable periodic coal feed rate which, in turn, resulted in periodic variation of the air/fuel ratio in the combustion zone. The desired coal feed rate is established by controlling the rate of rotation of the auger. Thus, by controlling the coal and air supply rates, testing at different air/fuel ratios can be performed.

The measurements performed during a given test are described in Fig. 1. A pressure transducer at the midpoint of the combustor, where the acoustic pressure antinode is located, measures the amplitude of the pulsations. The gas temperatures near the entrance to the combustor, above the combustion bed and below the exit plane are measured with thermocouples as shown. Probes for sampling gas and particulates from the exhaust flow are located just below the combustor exit plane, see Fig. 3. A schematic of the exhaust gas and particulate sampling trains is presented in Fig. 4. The exhaust gas is sampled continuously and analyzed to determine the CO, CO_2, NO_x, SO_2 and O_2 concentrations in the exhaust flow. Not shown in the figure is an O_2 analyzer which was recently added to the gas analysis system. Particulate sampling is performed isokinetically to determine the exhaust flow particulates concentration during selected time periods of a test. A mini computer based data acquisition and storage system which digitizes the analog test data and stores it for post test analysis and plotting was developed. Consequently, the performance of the combustor throughout the duration of a test can be continuously recorded and analyzed. More details about the developed instrumentation system can be found in a recently completed Ph.D. thesis[2] which was performed as part of this research program.

III. RESULTS

Todate, the performance of the combustor was evaluated using bituminous and subbituminous coals whose properties are described in Table I below. However, since most of the testing was conducted with the bituminous coal, only results obtained with this coal will be considered in detail herein. These data will be supplemented with a qualitative discussion of the results obtained to date with the subbituminous whose testing is still in progress.

The stoichiometric air/fuel ratios for these coals were determined under the assumption that all carbon reacts to form carbon dioxide, all sulphur reacts to form sulphur dioxide, and all hydrogen reacts to form water vapor.

Tests conducted under this study to date have demonstrated that unpulverized coal can be burned continuously under a pulsating mode of combustion in the developed Rijke type combustor. Pulsating operating is

Table I

Properties of the Bituminous and Subbituminous Coals Tested Under This Program

		Bituminous Coal	Subbituminous Coal
Proximate Analysis	Fixed C	55.38%	34.53%
	Volatile	35.13%	36.82%
	S	1.55%	0.88%
	A	7.39%	8.86%
	M	2.10%	19.79%
	Heating Value	13,801 Btu/lb	9,402 Btu/lb
Ultimate Analysis	C	76.46%	54.47%
	H	4.88%	3.82%
	N	1.39%	0.64%
	O	6.09%	11.18%
Stoichiometric Air/Fuel Ratio		10.35	7.18

achieved consistently within minutes after igniting the fuel in the bed.*
Completely different characteristics of burning under pulsating and non pulsating conditions were observed.

Under the pulsating mode of operation, the flames above the combustion bed were relatively short and exhibited an intense agitation. The coal in the bed was totally immersed in the flames and "dancing", downward pointing flamelets were anchored to the bottom of the combustion bed. In addition, the exhaust flow appeared clear and smoke free. Finally, the combustor wall in the region of the combustion bed heated up very rapidly after ignition to a glowing red condition.

During the course of this investigation it has been noted that opening one or more half inch holes in the combustor wall approximately one foot above the combustion bed caused a transition to nonpulsating burning. When the pulsations stopped the flames became relatively long, sometimes reaching the top of the 9 foot combustor, and the base of the flames appeared to be attached to the coal at some distance above the metal grid which supported the bed. Also, the flames lacked the agitation observed during pulsating operation and rapid accumulation of unburned coal occurred

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* It should be pointed out that the characteristics of the pulsating combustion operation depend upon the ignition method in such a system without mechanical coal distribution mechanism . "Good" start up which required following a developed ignition procedure, assured proper, "steady state" pulsating combustion operation while poor ignition often resulted in "unsteady" pulsating operation which was characterized by amplitude variations and rapid ash accumulation.

in the bed. The exhaust gases were smoky and the wall surrounding the burning bed was not red hot as it was during operations with pulsations.

The observed qualitative differences between the pulsating and nonpulsating modes of operation support arguments in the literature which claim that the presence of pulsations improves the efficiencies of the combustion and heat transfer processes. The oscillatory flow in the combustion zone improves the mixing between the oxidizer and the fuel, which results in a higher reaction rate and a more complete combustion process. The latter is responsible for the observed short flames and the clear and apparently smoke free exhaust gases. The back-and-forth velocity oscillations in the combustion zone are also responsible for the presence of the highly agitated flames which engulf the coal in the bed and for the flamelets that extend downward from the bottom of the metal grid which supports the bed. Finally, support for the intensification of heat transfer under pulsating conditions is provided by the observed rapid heat-up of the combustor wall surrounding the reaction zone.

A typical set of test data measured during a test is presented in Figs. 5 through 10. The pressure amplitude shown in Fig. 5, remains relatively constant with time. However, the data exhibits step-function changes because of round-off errors in the data reduction program. The program is currently being modified to reduce the round-off errors and provide a more representative output of the pressure data. Figures 6, 7, 8 and 9 show the time variations of the exhaust flow concentrations of CO, CO_2, NO_x and SO_2, respectively. The fluctuations in the measured concentrations have been correlated with the periodic discharges of coal from the rotating auger feed system. Modifications to the coal feed system have recently been completed resulting in a more uniform coal feed rate which, in turn, decreased the fluctuations in the measured concentrations.

Figure 10 shows the time variations of the temperatures at different combustor locations. Temperature T_2 was measured 1.5 ft. above the combustion bed and the remaining temperatures were measured 1 ft below the combustor exit plane, at the radial locations shown in Fig. 11. The temperature data indicate that temperatures inside the combustor are relatively low. For example, note that T_2, the temperature 1.5 ft above the burning bed, is only around $1400^{o}F$, which is considerably lower than the $3000^{o}F$ temperatures which are expected in coal combustors.[10,11] The reasons for the measured low temperatures is that the developed steel combustor was not insulated and the presence of acoustic velocity oscillations resulted in high heat losses through the combustor walls.

The performance under each test condition was determined from time averages, over the duration of the test, of data similar to that presented in Figs. 5 through 10. Typical results are presented herein and more data can be found in Ref. 2. The following set of data was obtained with the inclined auger on the left of Fig. 2. These tests were conducted with a nominal coal feed rate of 50 gr/min and different air/fuel ratios. The measured CO and CO_2 concentrations together with the air/fuel ratio were used to determine the combustor efficiency η. Typical dependence of η upon the nondimensional air/fuel ratio (i.e., α) is presented in Fig. 12. As expected,

η increases with α and it is larger than 96% for α = 1.15, which compares very favorably with coal burning stokers. The latter usually operate at 20-30% excess air and typically have a carbon loss of 4 to 8%, depending on the amount of reinjection.[11] No reinjection of unburned refuse was performed in any of the experiments of this investigation.

Figure 13 shows the dependence of the average dB level of oscillations upon the nondimensional air/fuel ratio. The data show that maximum amplitudes occur near stoichiometric air/fuel ratio. It is believed that this behavior is related to the magnitude of the temperature change, from cold air to hot combustion products, which occurs at the bed. This temperature jump is maximum near stoichiometric operation and it has been shown[12,13,14] that the efficiency of driving acoustic waves in tubes with a temperature jump (see Fig. 18) increases when the magnitude of the temperature jump increases. The results shown in Fig. 13 also indicate that a Rijke type combustor can be operated at high amplitudes of pulsation with little excess air. This result suggests that systems utilizing such a combustor should exhibit high thermal efficiencies. Furthermore, Fig. 13 shows that pulsating combustion of coal is possible in a Rijke type combustor over a wide range of air/fuel ratios. Since for $\alpha < 1$, the exhaust flow contains combustibles, these data suggest that the developed pulsating combustor could possibly be used as a coal gasifier.

For the following series of tests the inclined auger was replaced by the horizontal auger on the right of Fig. 2. The new auger provided a much more uniform coal feed rate into the combustion bed and it was used to investigate the dependence of the combustor performance upon the coal feed rate for fixed values of the normalized air/fuel ratio. Two normalized air/fuel ratios were tested; that is, $\alpha = 1.00$ and $\alpha = 1.13$. The coal feed rate was increased from 36 to 90 gr/min (28.9 to 72.2 lb/ft^2hr) in steps of approximately 8-10 gr/min (6.4 - 8.0 lb/ft^2hr).

Results obtained in this series of tests are presented in Figs. 14 through 17. Figure 14 describes the dependence of the combustion efficiency η upon the coal feed rate. It shows that for $\alpha = 1.00$, the maximum efficiency is 92% and it is equal or larger than 90% for feed rates between 42.1 and 56.1 lb/ft^2hr. On the other hand, when x = 1.13, $\eta > 95\%$ for coal feed rates in the range 42 - 60 lb/ft^2hr, with η reaching a maximum value of 97%. Again, these results compare very favorably with characteristic combustion efficiencies of stokers.[11]

The trends indicated by the data presented in Fig. 14 can be understood with the aid of the results presented in Fig. 15 which describe the dependence of the average dB level of pulsations on the coal feed rate. Figure 15 shows that the dB level of pulsations increases monotonically with an increase in the coal feed rate for a constant α. Furthermore, as expected (see Fig. 15), the amplitudes produced under stoichiometric conditions are, in general, larger than those for $\alpha = 1.13$. The lower acoustic pressure amplitudes at the lower feed rates result in a reduction in the efficiency of mixing between the oxidizer and the fuel which is probably the reason for the decrease in the observed combustion efficiencies (see Fig. 14). As the fuel feed rate increases (for a fixed air/fuel ratio) both the dB level of pulsations and the steady air velocity increase. An analysis performed under this program has shown that an increase in the dB sound level would result in the expulsion of small particles out of the combustor. This effect together with the increase in the steady state velocity, which is required to keep constant when the fuel feed rate increases, would tend to cause an increase in the elutriation of small unburned coal particles from the combustor which, in turn, should result in a decrease in the combustion efficiency of the combustor. Indeed, the presence of coal particles in the exhaust flow was observed in tests conducted at the higher fuel feed rates. The presence of burning particles in the exhaust flow is believed to be the main cause of the observed decrease in combustion efficiencies at the higher coal feed rates.

The combustion efficiency data were used to determine the combustor heat release rate as function of the coal feed rate. These results are shown in Fig. 16. The heat release rates, Q, in Btu/ft^{2}hr, were computed from the following formula:

$$Q = \frac{Hv \times m_F \times \eta}{A} = 110.4\ m_F\ \eta$$

where m_F is the coal feed rate (in gr/min), η the combustion efficiency, Hv the heating value of the coal (Btu/lb) and A the cross sectional area of the combustor (ft^2). Figure 16 shows that a maximum heat release rate of approximately 0.87 MBtu/ft^{2}hr was attained; a value which is higher or comparable to heat release rates of other state-of-the-art combustors.[11]

The dependence of NO_x formation upon the coal feed rate is presented in Fig. 17 for different values of m_F. For comparison with the government's New Source Performance Standards (NSPS) of 1971 and 1979 the data are expressed in terms of lb NO_x per 10^6 Btu. Figure 17 shows that for $\alpha = 1.13$ the NO_x production slightly exceeds the 1979 NSPS standard for feed rates up to, approximately, 48 lb/ft^{2}hr with a higher production of NO_x occuring at higher feed rates. Figure 17 also indicates that for a given coal feed rate, the NO_x production increases with increased excess air (i.e., α) and it is below the 1979 NSPS standard for stoichiometric operation (i.e., $\alpha = 1$).

In what follows, some recent results obtained when the subbituminous coal (see Table I) was burned under pulsating conditions are briefly discussed. First, it would be useful to consider some of the differences between the two coals which might also help to explain some of the observed trends. Contrary to the bituminous coal, the subbituminous coal does not tend to cake which would reduce the possibility of this coal agglomerating on the bed. Since the heating value of the subbituminous coal is lower, less energy was supplied and released into the combustor for a given coal feed rate. This would result in lower temperatures in the combustor when subbituminous coal is burned. Finally, since these coals have different stoichiometric fuel/air ratios, the burning of a given amount of subbituminous coal requires less air than would be required for the burning of a comparable amount of bituminous coal. Less air would imply lower air velocities in the combustor which, in turn, would reduce elutriation.

Differences in the pulsating combustor performance resulting from burning subbituminous and bituminous coals at a feed rate of 50 gr/min and $\alpha = 1.13$ are presented in Table II below. One should note that when subbituminous coal is burned the percentages of particulate matter, carbon monoxide and nitrogen oxides in the exhaust flow are lower. In addition, the temperature in the combustor is lower, the dB level is higher and the combustion efficiency is higher. The tests with the subbituminous coal are currently in progress.

In summary, the results presented in this section demonstrate that coal can be burned efficiently in a Rijke type pulsating combustor. High combustion efficiencies were obtained in spite of the fact that the combustor was uninsulated, which resulted in high heat losses (which are recoverable) through the combustor walls and relatively low temperatures is the combustion zone. Furthermore, these high combustion efficiencies were achieved with the combustor operated with relatively little excess air (i.e., 13%). The NO_x production only slightly exceeded the 1979 NSPS standards for coal feed rates up to 48 lb/ft^2 hr and it decreased when the excess air was decreased. Finally, it has been demonstrated that both bituminous and subbituminous coals can be burned in the developed pulsating combustor and preliminary data indicate that better performance can be attained when burning subbituminous coals.

Table II

Comparison of the Performance of the Pulsating Combustor when burning Bituminous and Subbituminous Coals with m_F = 50 gr/min and α = 1.13.

	Bituminous Coal	Subbituminous Coal
Particulates in the exhaust flow, percent of carbon in feed rate	1.2	0.1
Exhaust flow carbon monoxide concentration, percent	0.8	.0353
Exhaust flow NO_x concentration, ppm	460	350
Exhaust flow SO_2 concentraction, ppm	900	870
Temperature 1½ ft above the combustion bed, ^oF	1500^oF	1400^oF
Combustion efficiency, percent	94	96.1
Sound pressure level, dB	156.0	157.1

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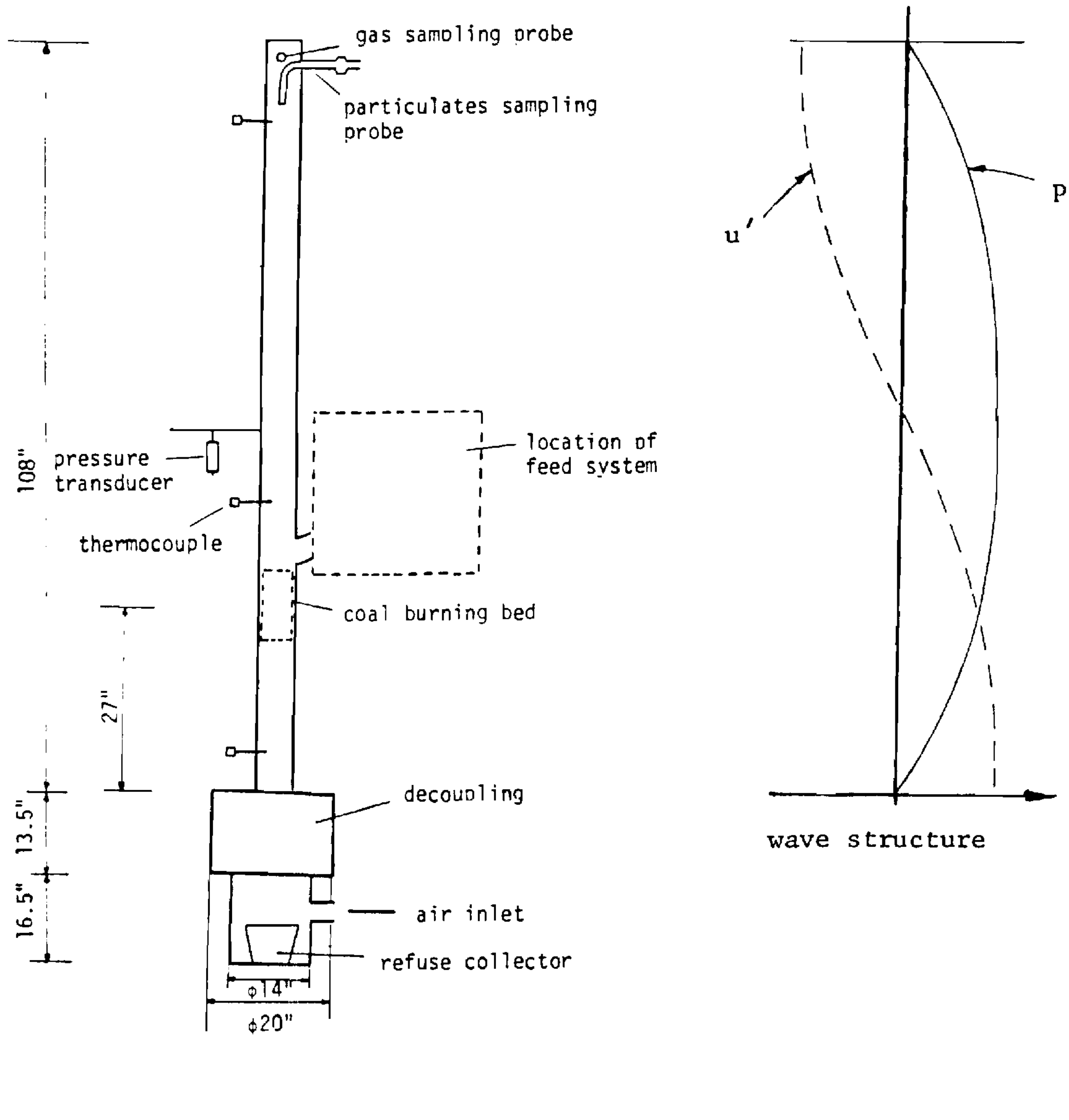
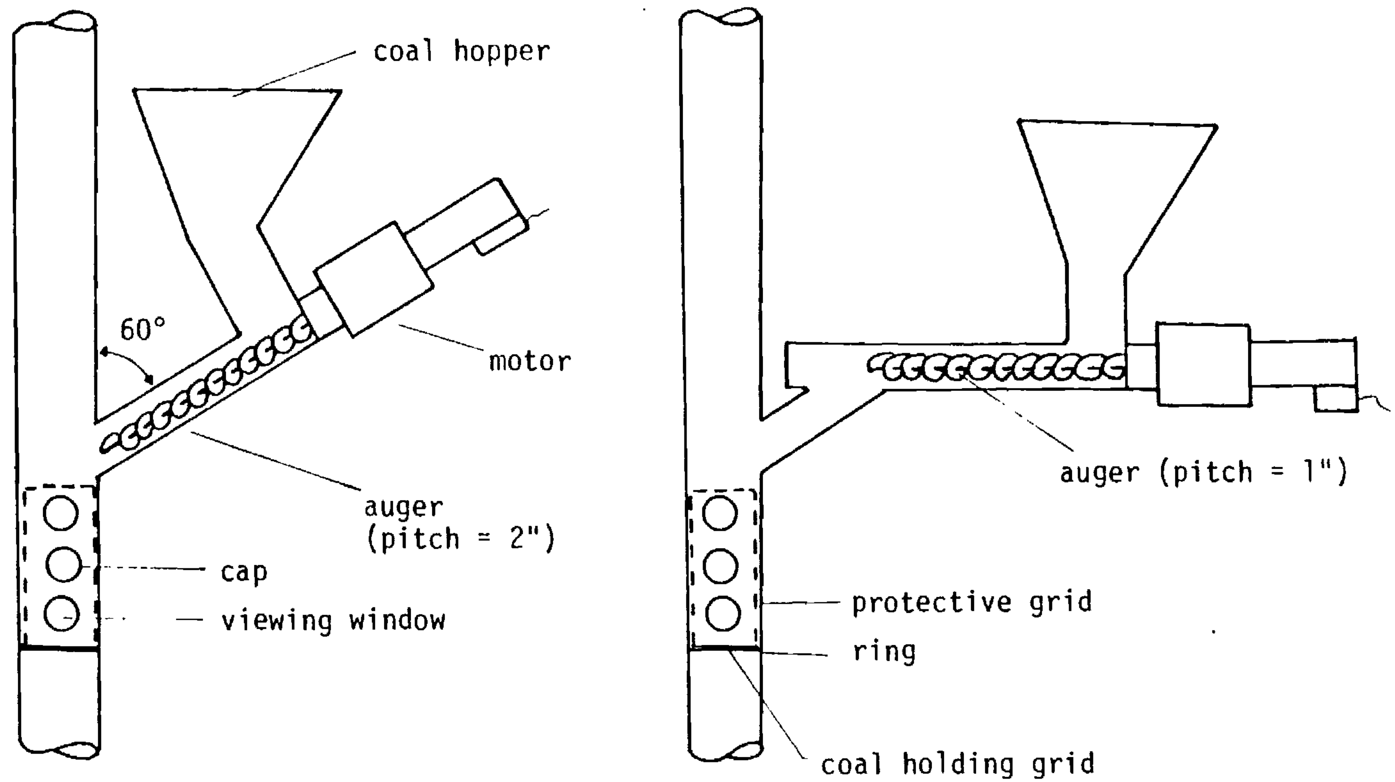


Figure 1. Schematic of the Rijke Tube Pulsating Combustor and Wave Structure.



Inclined Auger

Horizontal Auger

Figure 2. Schematic of the Auger Type Feed System (Inclined and Horizontal Auger).

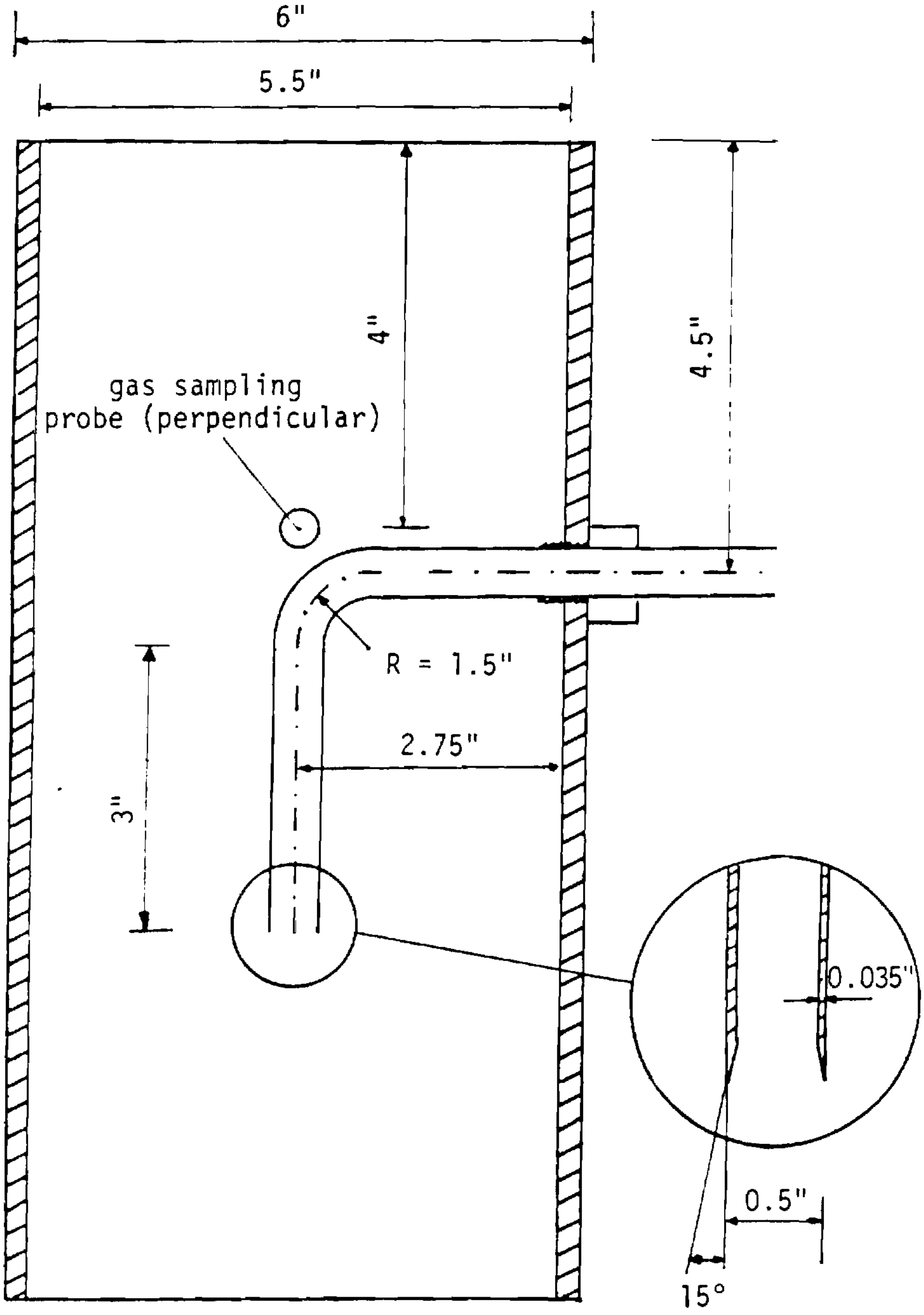


Figure 3. Particulates Sampling Probe and its Dimensions.

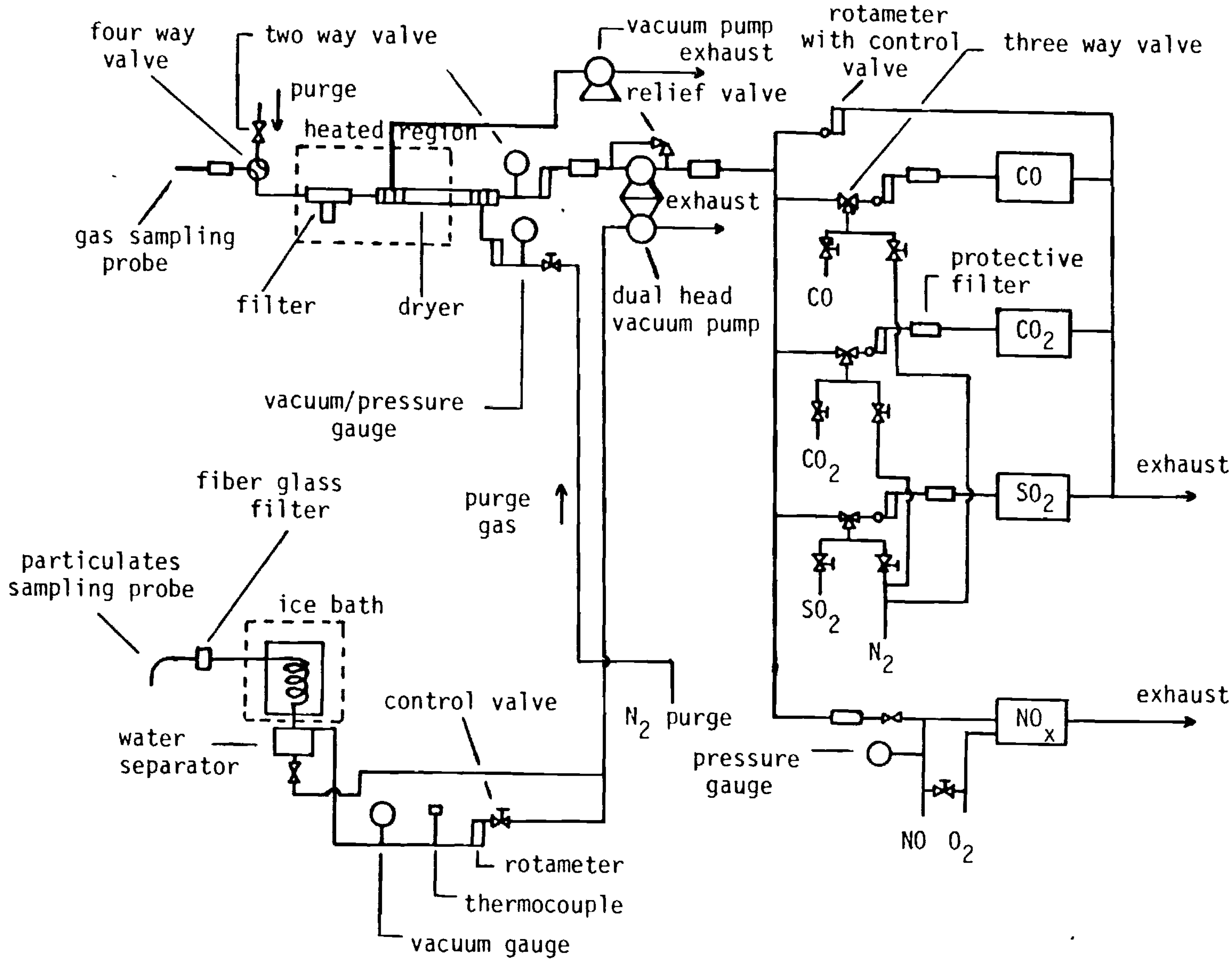


Figure 4. Schematic of the Modified Gas - Particulates Sampling Train.

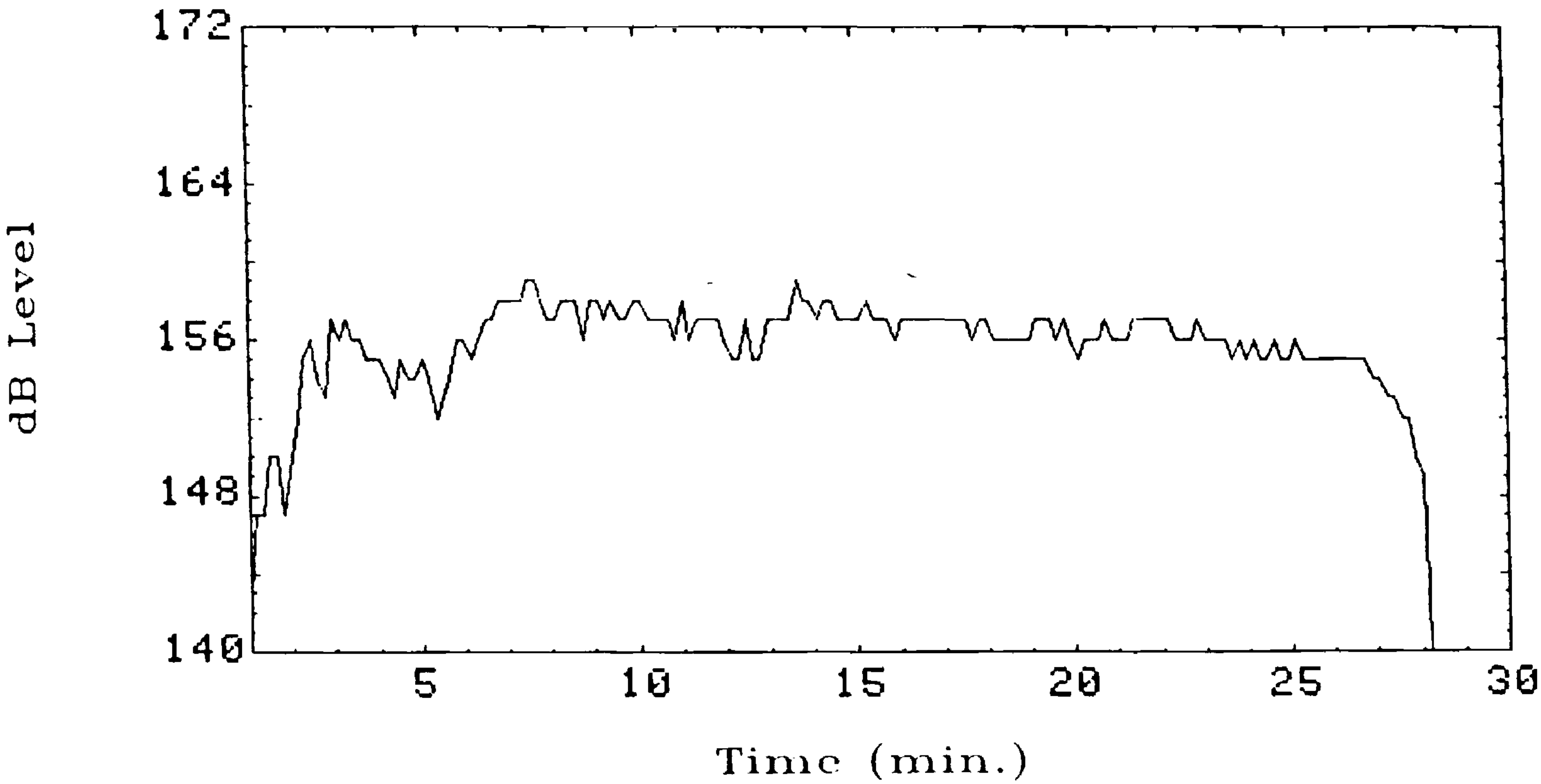


Figure 5. Time Variation of the dB Level of Oscillations (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

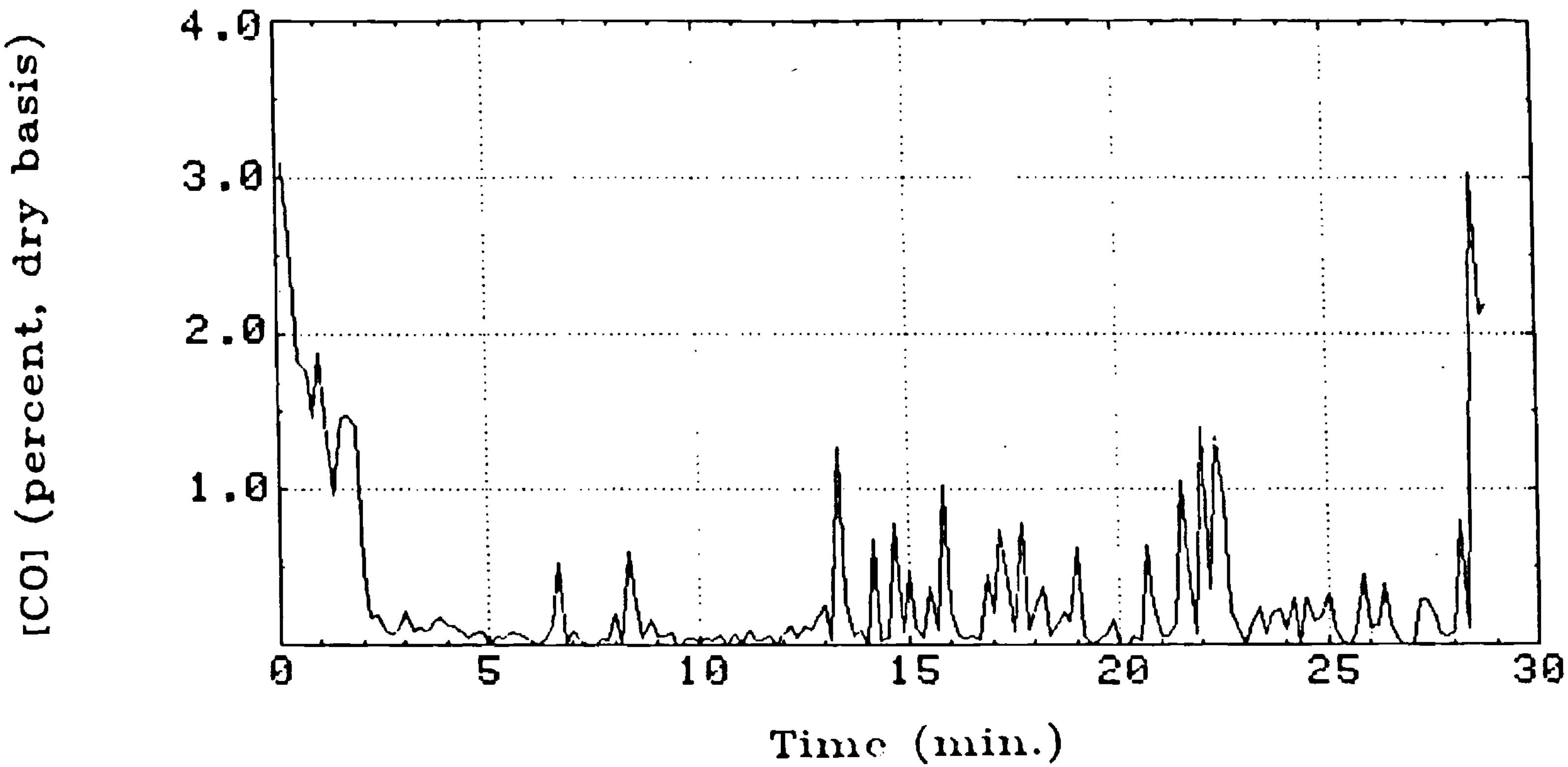


Figure 6. Time Variation of the CO Concentration (m_F = 29.9 lb/sqft. hr., (Alpha = 1.13).

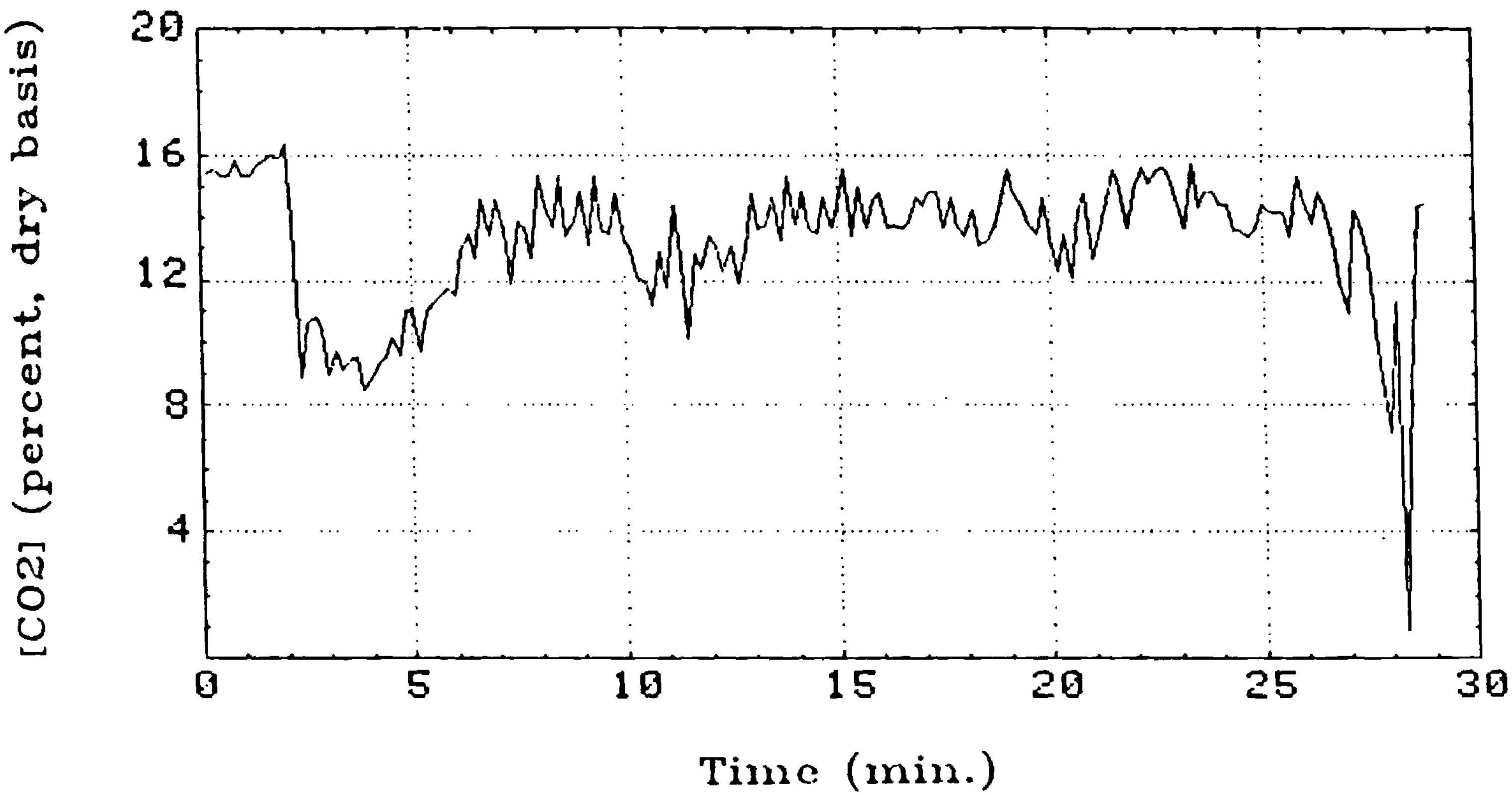


Figure 7. Time Variation of the CO_2 Concentration (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

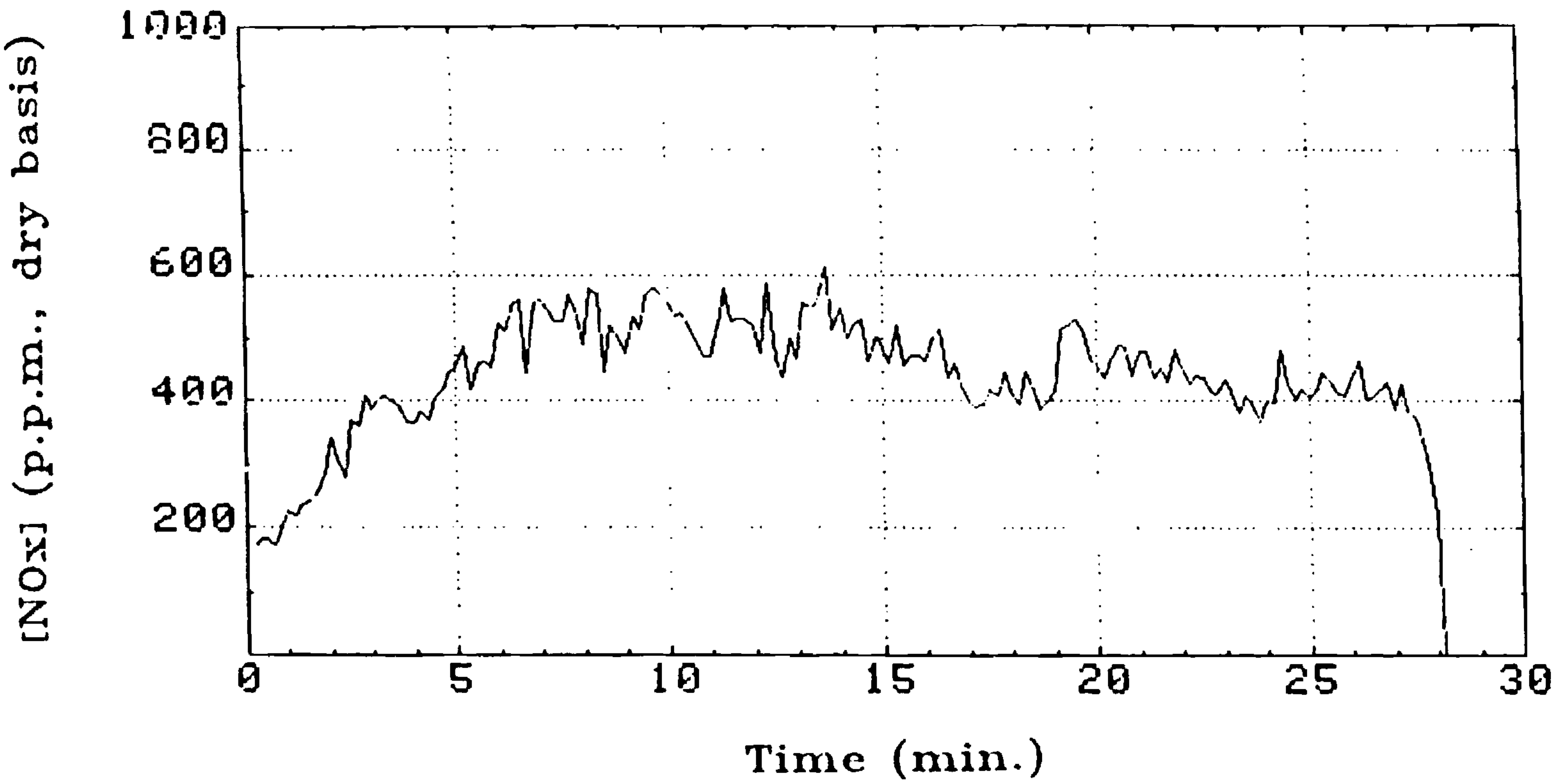


Figure 8. Time Variation of the NO_x Concentration (m_F = 29.9 lb/sqft. hr., (Alpha = 1.13).

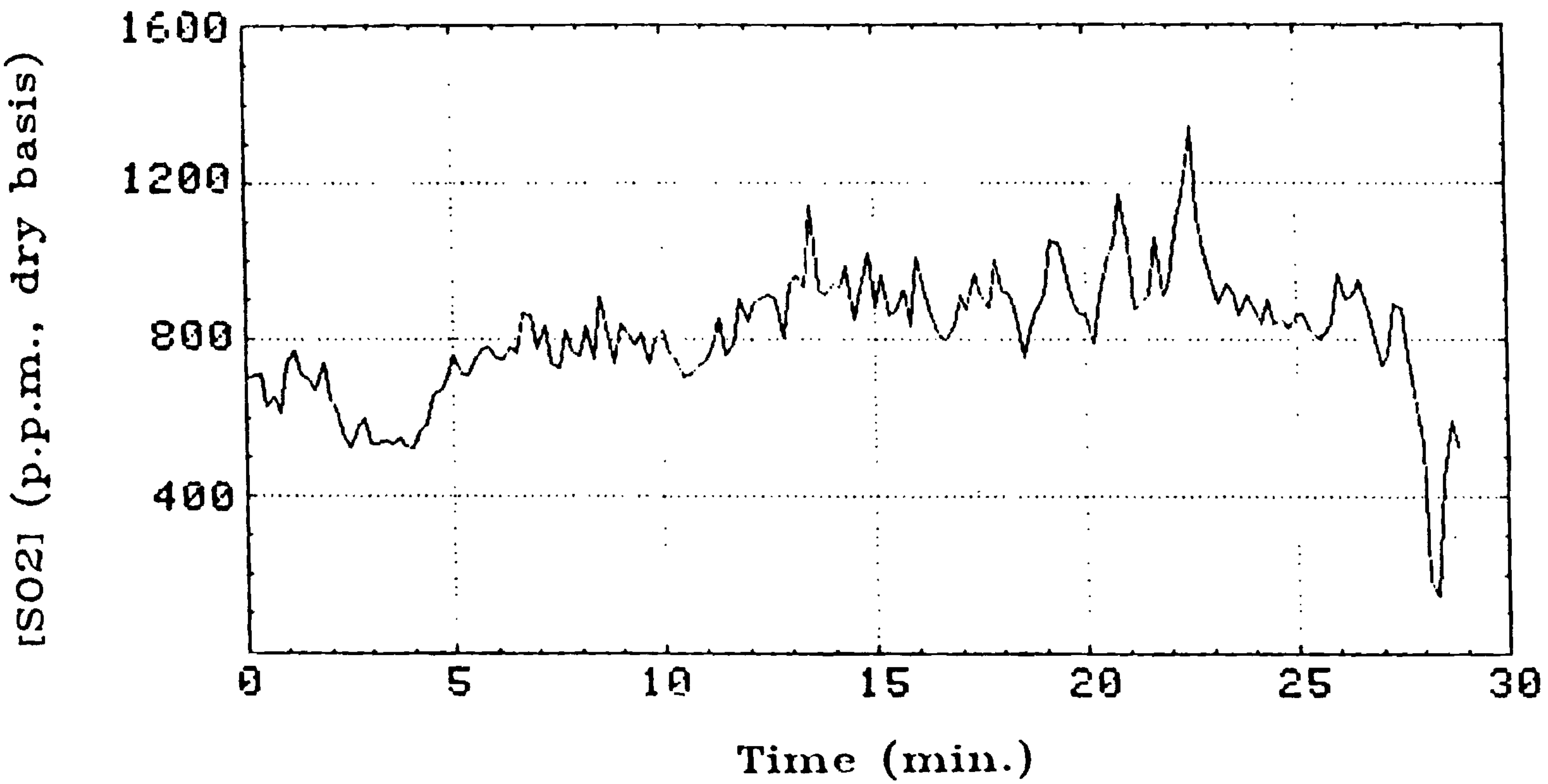


Figure 9. Time Variation of the SO_2 Concentration (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

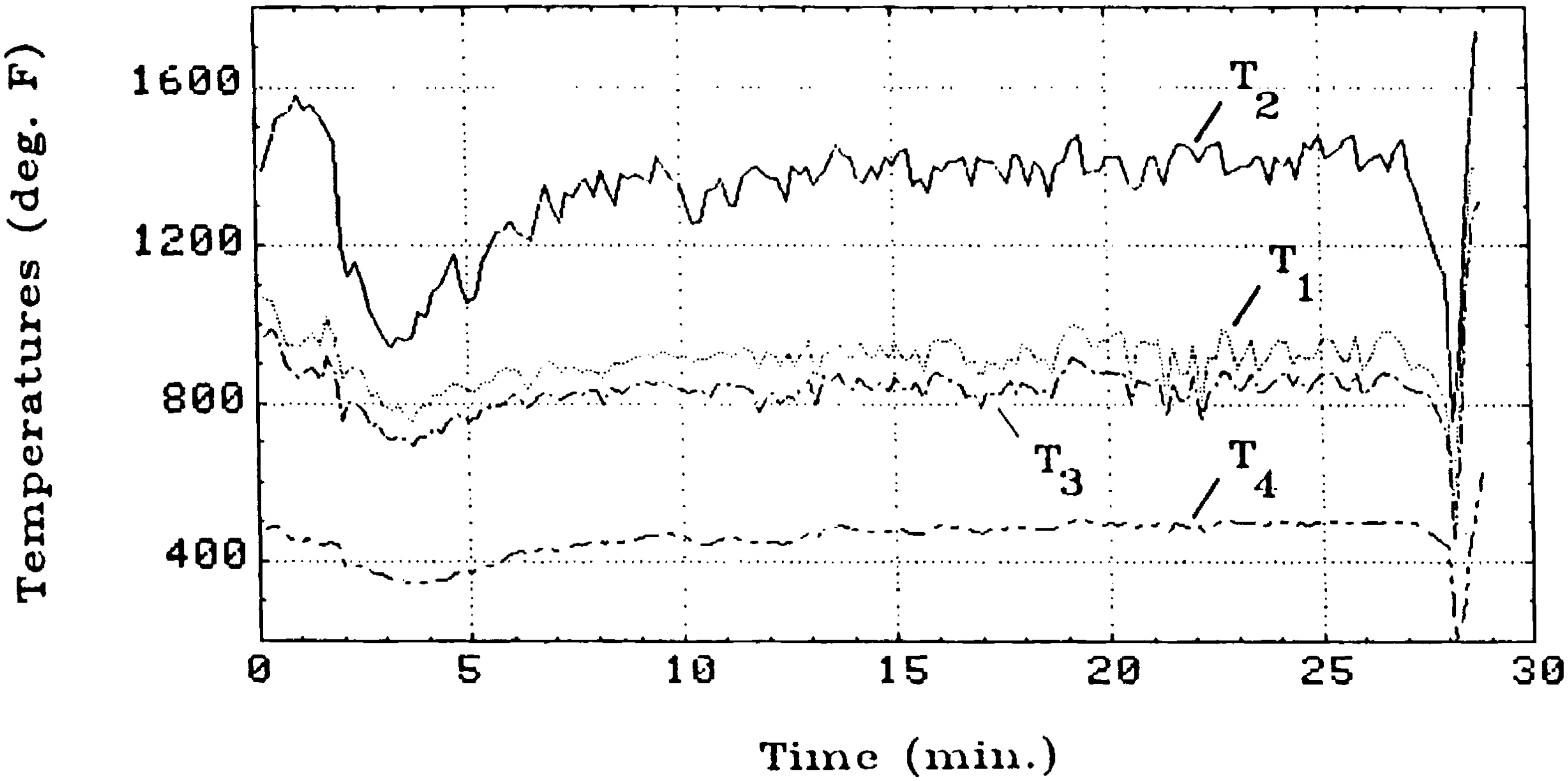


Figure 10. Time Variation of Temperatures (m_F = 29.9 lb/sqft. hr., Alpha = 1.13).

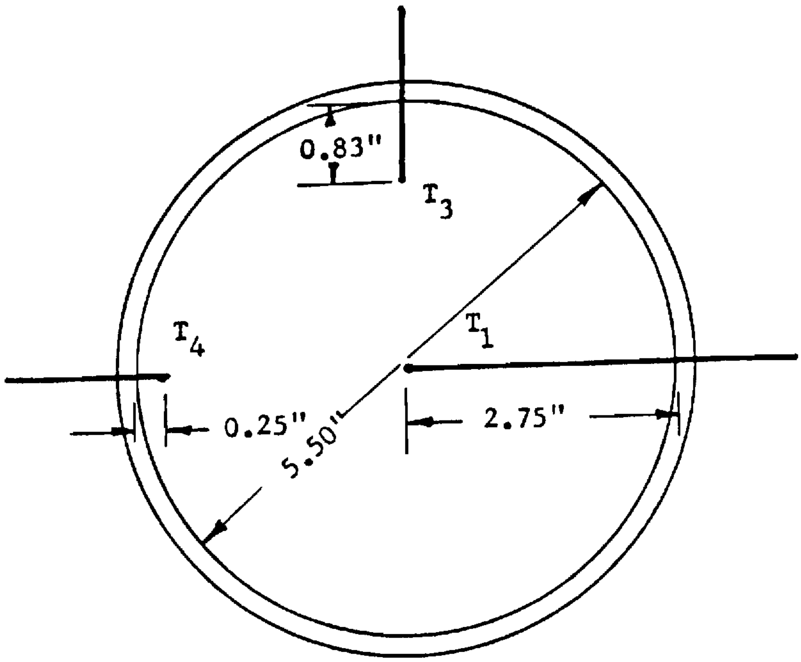


Figure 11. Locations of Thermocouples T_1, T_3, and T_4.

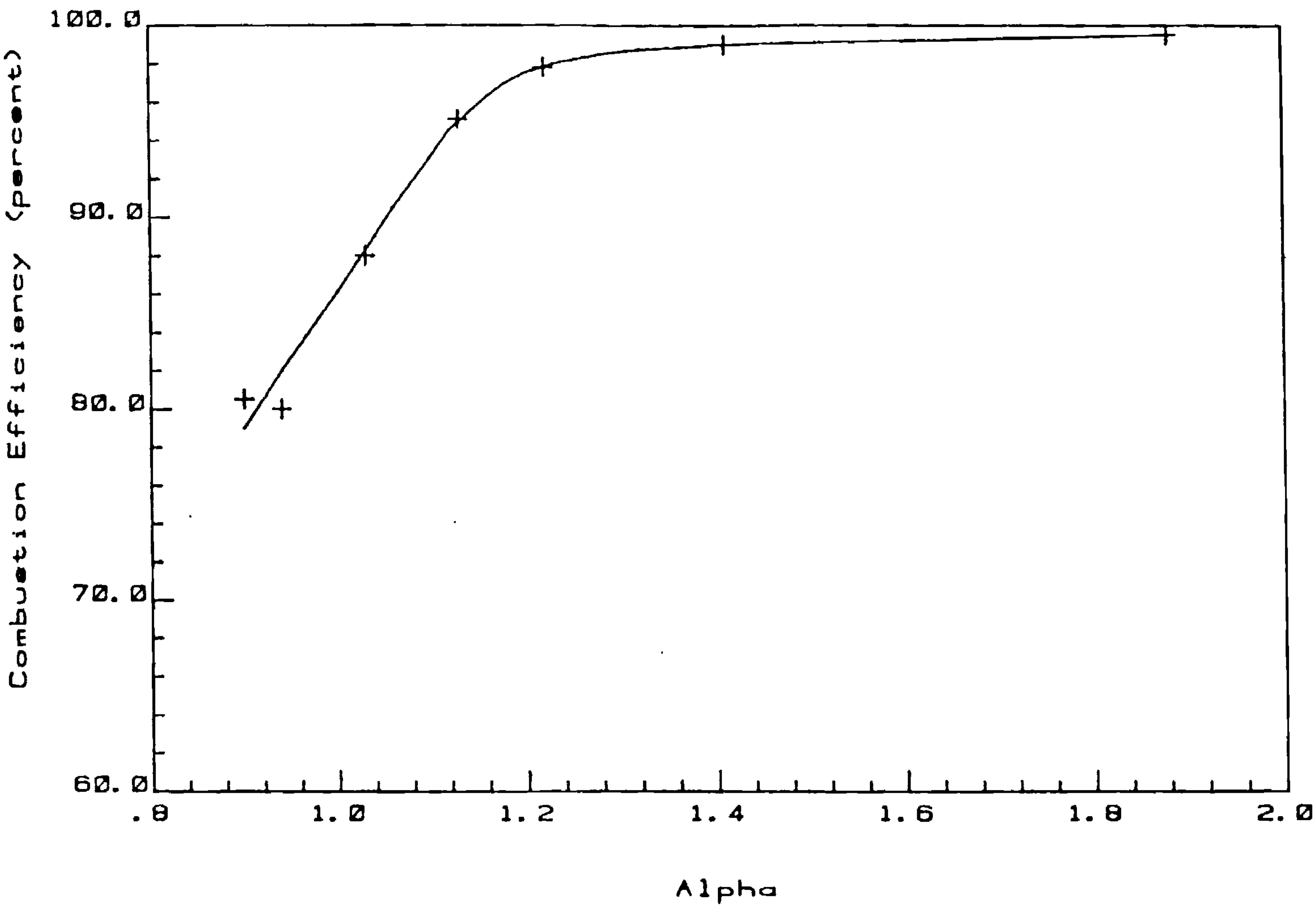


Figure 12. Dependence of the Average Combustion Efficiency upon the Normalized Air/Fuel Ratio (m_F = 40.1 lb/sqft. hr.).

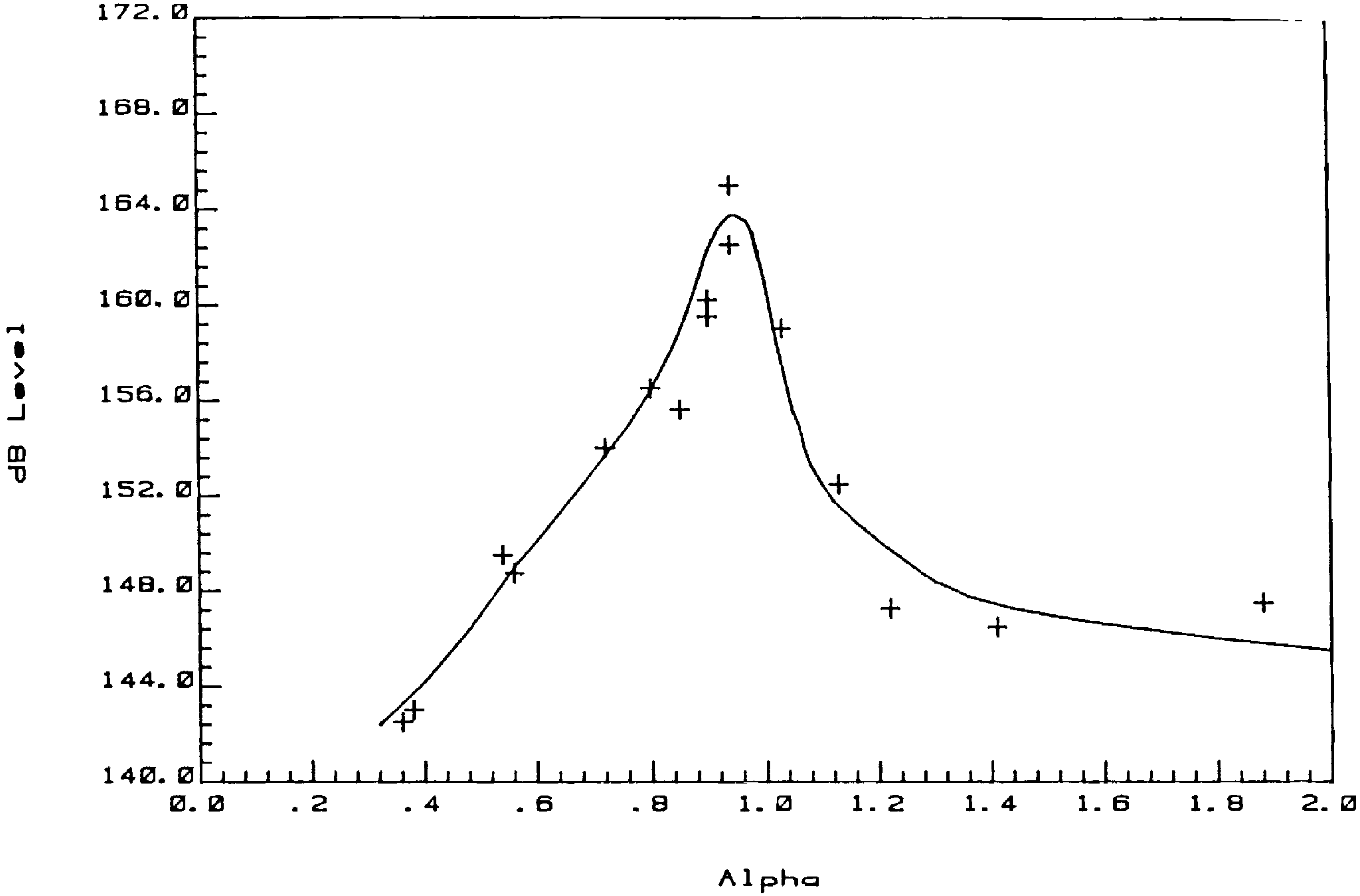


Figure 13. Dependence of the Average dB Level of Pulsations upon the Normalized Air/Fuel Ratio (m_F = 40.1 lb/sqft. hr).

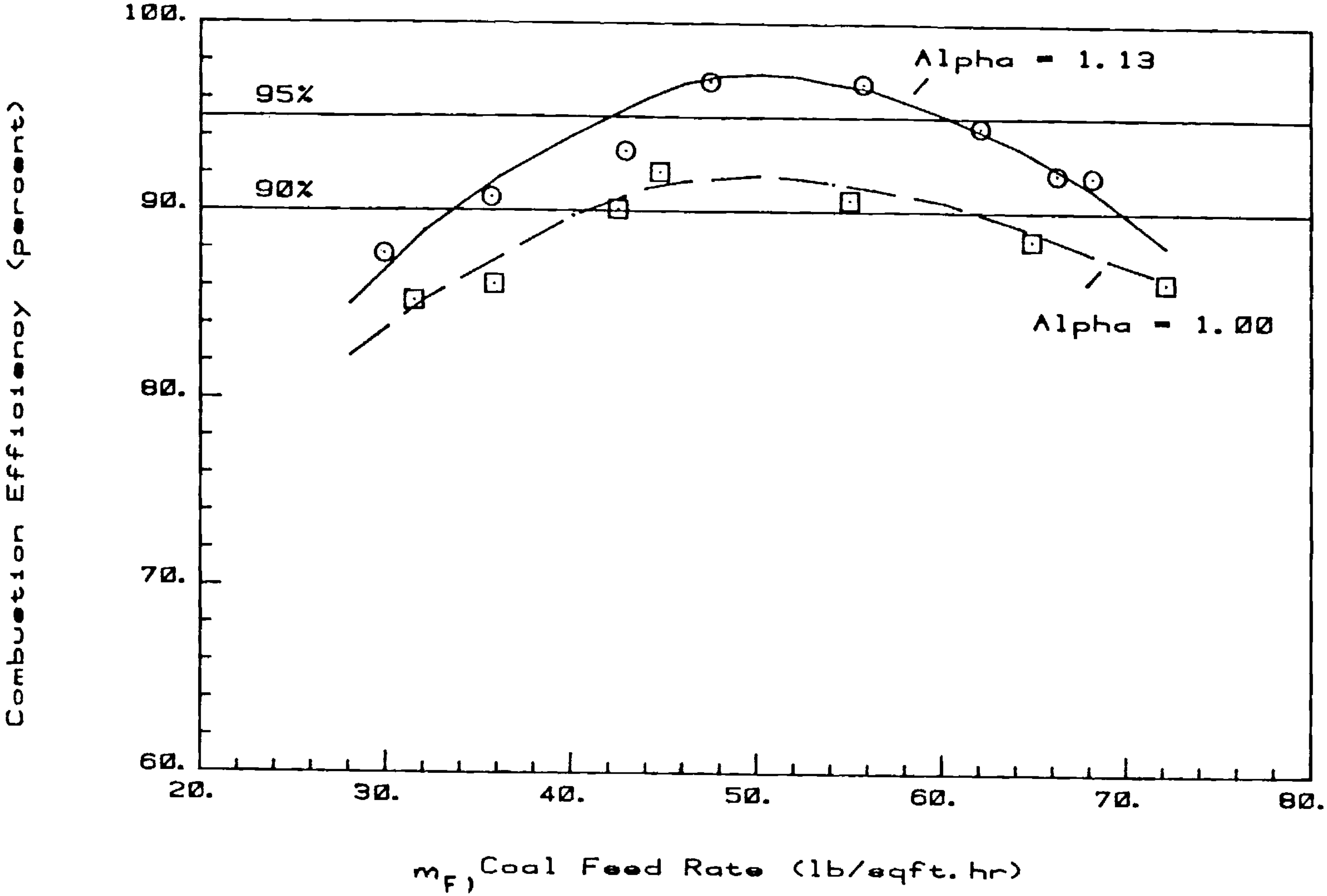


Figure 14. Dependence of the Average Combustion Efficiency upon the Coal Feed Rate.

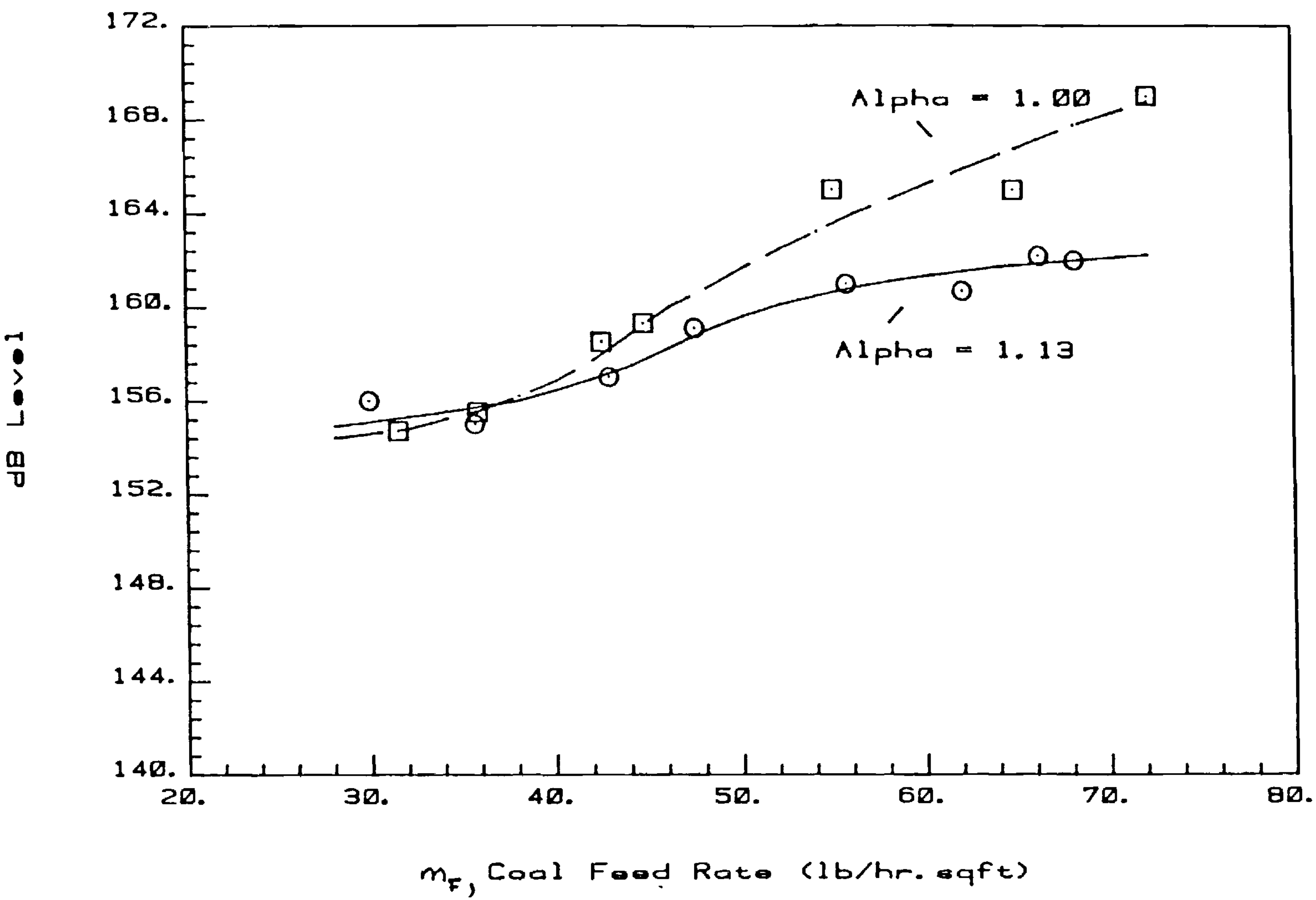


Figure 15. Dependence of the Average dB Level of Pulsations upon the Coal Feed Rate.

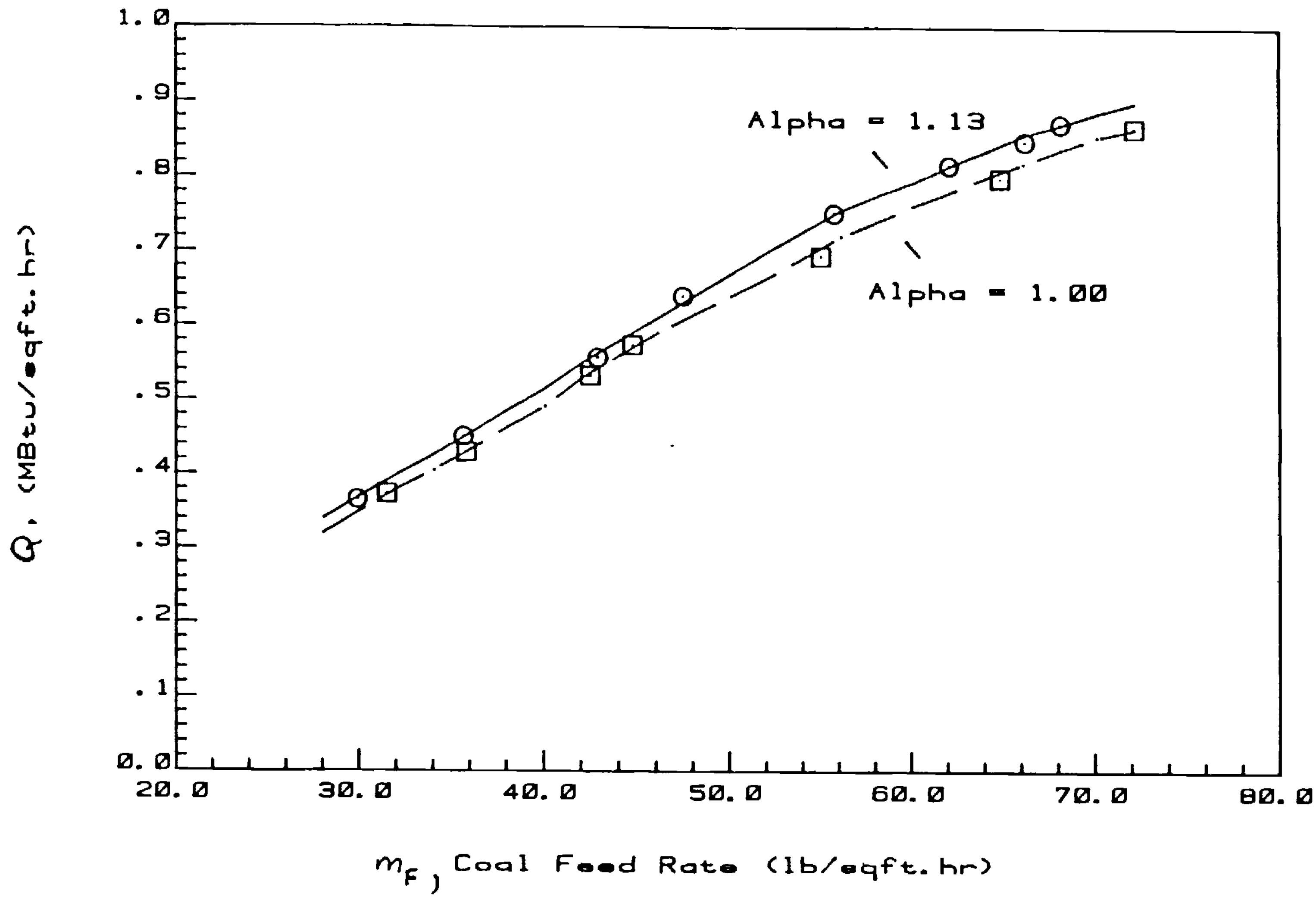


Figure 16. Dependence of the Average Heat Release Rate upon the Coal Feed Rate.

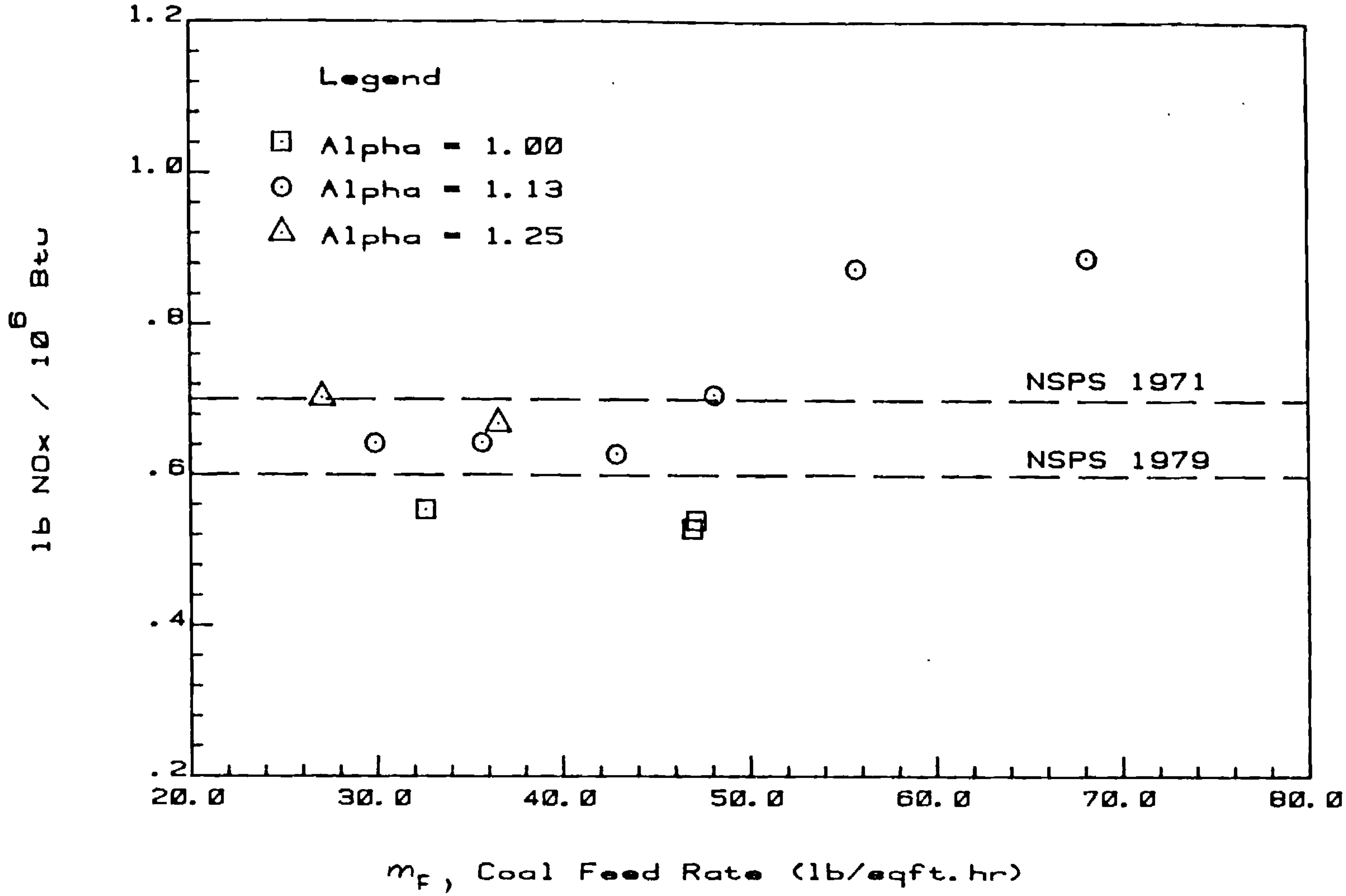


Figure 17. Dependence of the Average Amounts of Generated NO_x per 10^6 Btu upon the Coal Feed Rate.

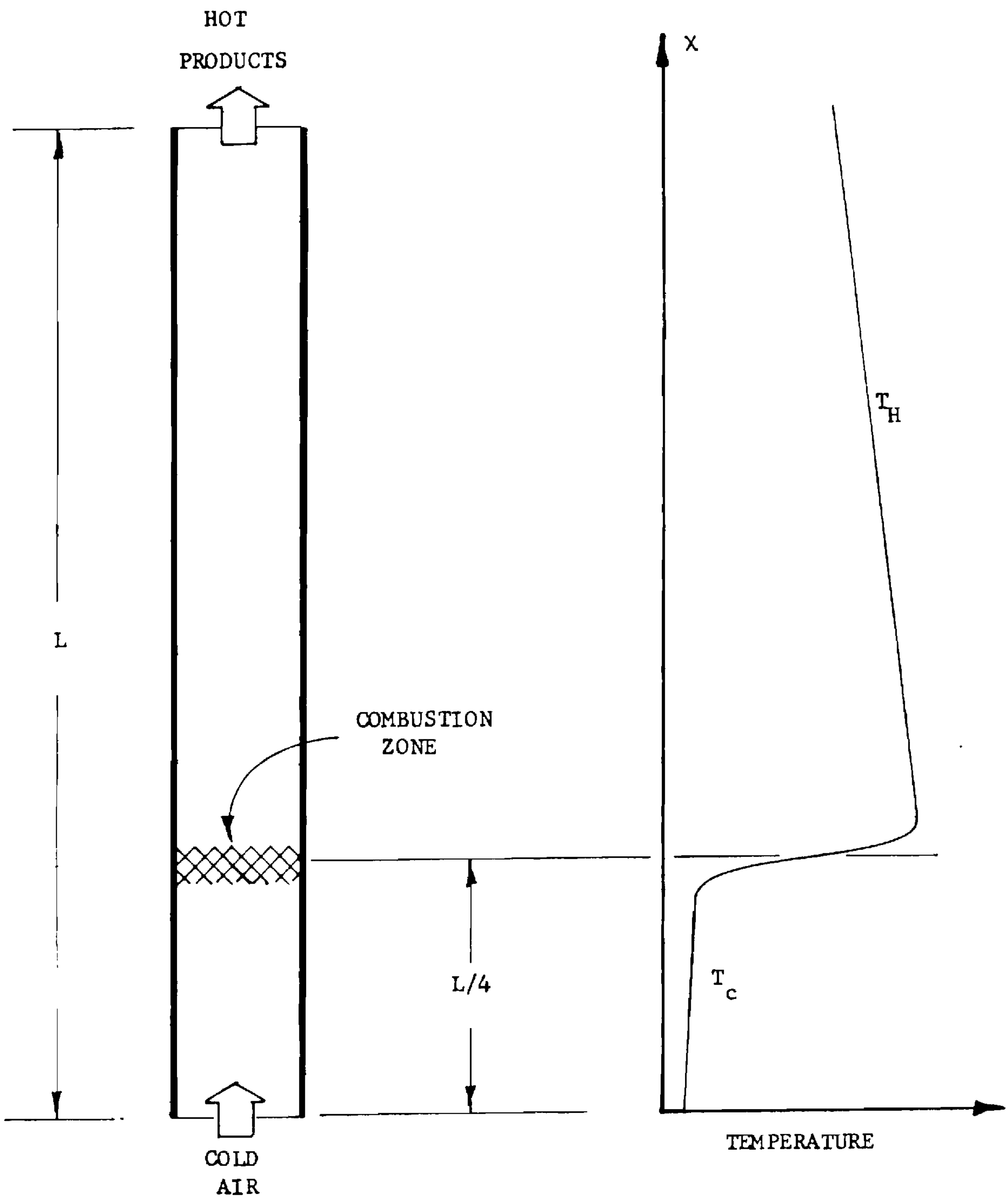


Figure 18. Dependence of Mean Flow Temperature upon Position (χ).